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INVESTIGATION OF DIESEL FUEL - ALCOHOL EMULSIONS

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DISCLAIMER

The contents of this report reflect the views of the contractor and not necessarily the official views of the Department of Energy, Mines and Resources of the Federal Government of Canada.

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The investigation of Diesel Fuel-Alcohol Emulsions has been carried out under a contract awarded by the Department of Supply and Services on behalf of the Department of Energy, Mines and Resources. The help of EMR staff, and NRC staff in carrying out the work is gratefully acknowledged.

EXECUTIVE SUMMARY

The performance of a new emulsifier technology using the proprietary emulsifier "Dalco" was investigated. A total of 23 different formulations using varying quantities of diesel, methanol, water, Dalco, and ignition improvers and smoke supressants were tested in a four cylinder Cummins engine. Tests were carried out at five steady state conditions. Engine performance, combustion characteristics and emissions were measured at each point for the 23 formulations which included Diesel #1, Diesel #2, and a 1990 Diesel as baseline fuels. The physical and chemical properties of the fuels were also established.

It was concluded that certain useful methanol or water additions to diesel fuel can be made using the Dalco emulsifier. The aqueous emulsions have demonstrated that inorganic salts may be incorporated into formulations which may provide a low cost means to improve blend cetane values and/or reduce particulate emissions. Future work should concentrate on low level methanol or water additions to diesel fuel, reduction in the quantity of emulsifier needed (to improve blend economics) and on testing selected compositions within EPA and industry approved testing regimes.

The current work did not aim to optimize operations with oxygenated fuel blends. Optimization could change the rankings assigned and inclusion of fuel cost criteria in the evaluation process would no doubt also alter the ranking.

EXECUTIVE SUMMARY (Cont'd)

Even without engine optimization a large number of methanol-diesel and water-diesel emulsions can outperform 1990 diesel in overall engine performance. Low level oxygenated blends may therefore provide a starting point for the eventual expansion of the diesel fuel pool to include blends containing water and methanol with up to 15% volume substitution.

It is significant that with one minor exception the four cylinder test engine started (admittedly at test cell temperatures of 15 to 20°C) and operated in a highly satisfactory manner on the prepared test fuels. It was also concluded that the stability of the fuels, while not yet perfected, was promising compared to other emulsifying systems.

It is recommended that:

- Future work concentrate on blend optimization now that the principle is established;
- To help in this optimization a substantial amount of additional data analysis is required;
- The follow-up test program must include transient testing;
- The follow-up test program should include testing of proposed catalyst trap systems to meet 1991 pollution levels in order to establish the effect of the formulations.

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1.0 INTRODUCTION

1.1 BACKGROUND

The most significant problems facing the producers and users of transport fuel are those concerned with diesel fuel. The future supply, quality and price of diesel fuel are concerns, as is the difficulty of modifying diesel engines to meet emerging stringent standards for vehicle emissions, especially for nitrogen oxides and particulates.

The addition of methanol to diesel fuel can extend the diesel supply and new formulations, which are emulsions of diesel-water and up to 30% methanol, have been demonstrated to be a potential route to the extension of diesel fuel availability. Similar emulsions from an Australian research organization appear to offer the best promise for the production of emulsions which are stable under Canadian environmental conditions. It is proposed to investigate the production, stability and performance of these diesel-alcohol emulsions in a typical Canadian bus/truck engine operated in a controlled laboratory engine test stand.

Investigation of the data on emissions from diesel-alcohol blend combustion shows that certain formulations reduce particulate production, and NOx is also reduced under other conditions. The diesel-alcohol-water emulsions will be formulated with other materials designed to further reduce particulate and NOx emissions. These fuels will also be evaluated for performance, stability and emissions. The data will be analyzed to determine the utility of the emulsions in highway vehicles. The cost/performance of the successful formulations will be determined and compared with those for diesel and alcohol based fuels when used separately as engine fuels.

1.2 OBJECTIVES

1.2.1 Technical Objective

To provide preliminary evaluation of the fuel economy and exhaust emissions of a range of formulated and optimized diesel-alcohol fuel emulsions.

1.2.2 Economic Objectives

a) To evaluate the commercial utility of middle distillate-aqueous methanol emulsions in applications now served by diesel fuel.

b) To select formulations which are expected to produce alternative (or extended) fuels with commercially valuable properties, such as low cost and reduced levels of combustion pollutants.

c) To develop end-use data that may assist Canada's alcohol producers to market their products in Canada and as exports.

d) To screen a limited number of fuel compositions that may demonstrate the potential of alcohol-diesel emulsions as a route to reduce Canadian industry's dependence on imported oil.

e) To demonstrate fuel options which may reduce fuel costs to Canadian industry. This can be achieved by partial substitution of diesel fuel by alcohols and by the use of alcohols to widen the range of petroleum fractions that may be used in the manufacture of diesel-like fuels.

1.2.3 Social Objectives

Implementation of the results of the investigation will realize the following objectives:

a) To reduce Canada's dependence on imported oil.

b) To preserve and create jobs in the manufacturing sector through expanded use of natural gas-derived methanol and/or biomass-derived ethanol.

c) To create a new industry in Canada based upon the technology of diesel-alcohol fuel emulsions.

d) To provide Canada's fuel and automotive manufacturing industries with new information and to maintain their access to fast-developing foreign alcohol fuel and engine technologies.

1.3 PROJECT METHODOLOGY

1.3.1 General

The investigation carried out was limited to the following: laboratory-scale tests of fuel formulations in a typical commercial bus/truck engine; the preparation and characterization of the formulations; and, limited cost-performance evaluations. Satisfactory results from this Phase 1 investigation may be followed by further development and testing of the most promising of formulated fuels (Phase 2) in 2-stroke and 4-stroke engines and (Phase 3) by large-scale field trials of selected fuel emulsions conducted in association with bus and truck fleet operators, a railway company, and utilities operating diesel electric generator sets.

1.3.2 Tasks (See Figure 1)

The following tasks were carried out:

- Meetings were held with the Scientific Authority and all participants to facilitate work, liaison and reporting.
- Preliminary bench-scale work was undertaken to formulate samples of diesel-alcohol-water emulsions, some with the addition of other components chosen to upgrade the cetane values, or reduce the particulate and NOx emissions on combustion.

The samples were characterized for viscosity, storage stability and calorific value (Parr bomb analyses conducted by the Analytical Laboratory of CANMET). The laboratory work was conducted partly at ORF and partly at NRC.

- 45 Imperial gallon samples of the formulations were prepared and stored for the combustion tests from ingredients supplied to ORF.

- The 20 samples of the selected diesel-alcohol emulsions were combusted in a typical 4-stroke urban truck engine. The engine was also run on 3 different pure diesel fuels without alcohol to provide the base-line data. The engine was run on a programmed dynamometer stand to produce engine performance maps and combustion parameters (peak cylinder pressure, maximum rate of pressure rise, and ignition delay), together with an accurate assessment of fuel consumption. The operating points chosen were such that subjective assessments could be made on the potential operability of the system. The exhaust gases were collected from each run and analyzed for soluble and insoluble particulates, unburnt hydrocarbons, CO_2, NO and NO2 content (hence total NOx) and carbon monoxide content. Analyzed data was submitted to the project management group for further analysis.

- Consultant company databases and the published literature were searched to generate a database on diesel-alcohol mixtures and their performance. The data will be interpreted to guide the proposed research in Phases 2 and 3.

- Data from the original investigations was interpreted to determine:

  - the best application for each composition investigated;
  - the commercial fleet and other end-uses which diesel fuel extension by methanol can provide;
  - the commercial value of the high cetane and low pollution compositions; and
  - analyze the cost/performance trade-offs.

1.4 ORGANIZATION OF THE REPORT

The report closely follows the previously outlined project methodology. Section 1.0 contains the Introduction and Section 2.0 summarizes the rationale for carrying out the work. In Section 3.0 previous work relevant to this investigation resulting from the literature search is reviewed.

Section 4.0 deals with the characterization of the fuel formulations and describes the formulation techniques together with the physical and chemical analysis results for the various blends. In Section

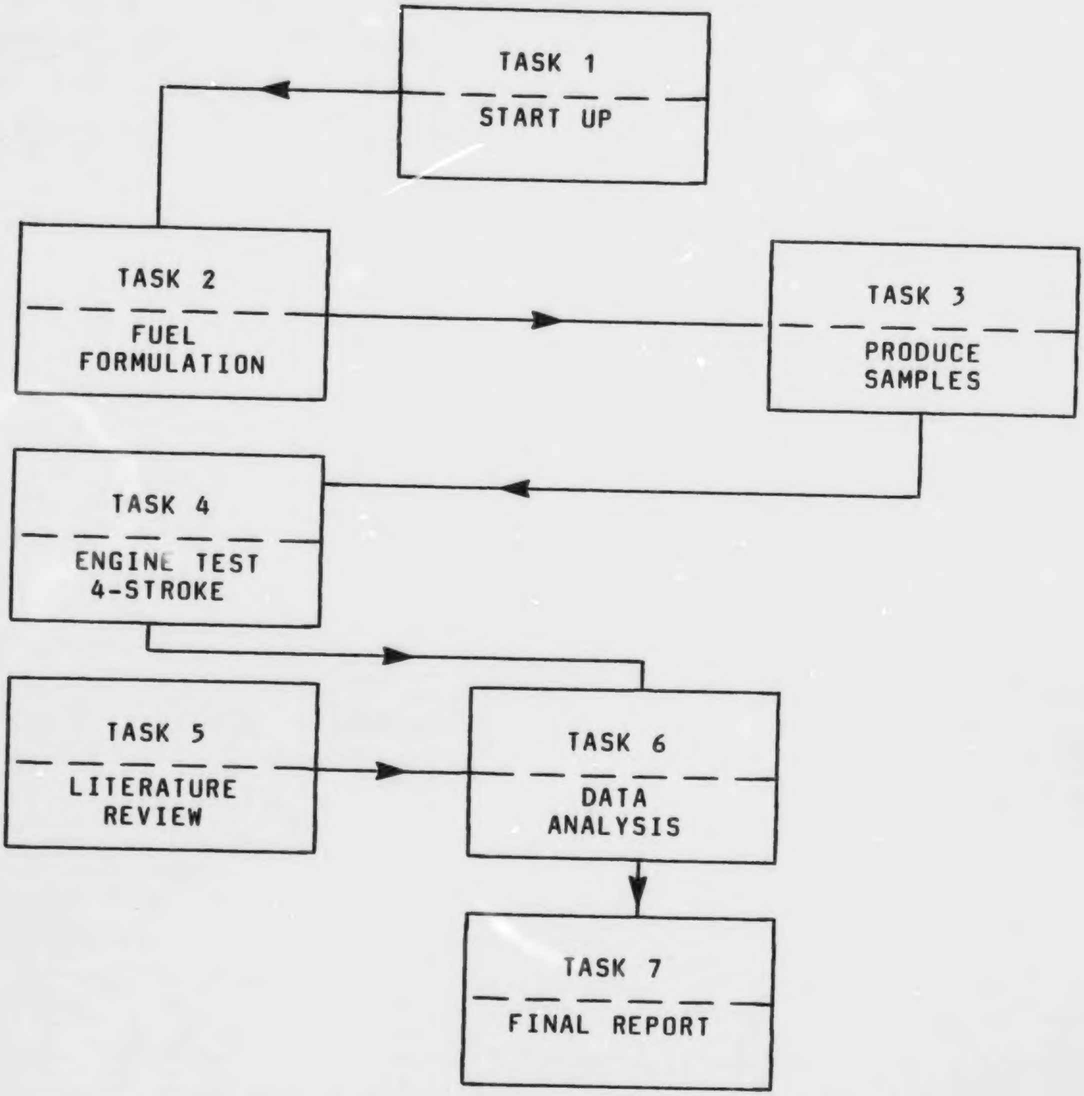
TASK 1
START UP
TASK 2
FUEL FORMULATION
TASK 3
PRODUCE SAMPLES
TASK 4
ENGINE TEST 4-STROKE
TASK 5
LITERATURE REVIEW
TASK 6
DATA ANALYSIS
TASK 7
FINAL REPORT

FIGURE 1: TASK NETWORK

5.0 the test equipment for the Engine Test program is described together with the data reduction process used to analyse the engine test results.

In Section 6.0 and 7.0 the results are discussed from technical and commercial aspects respectively. In Section 8.0 the conclusions and recommendations arising from the work are reported. The processed results of the emissions analysis are included as Attachment A. Raw data are provided in a second volume.

2.0 RATIONALE FOR THE PRESENT INVESTIGATION

2.1 DIESEL FUEL SUPPLY AND QUALITY PROBLEMS

The demand for diesel fuel in Canada increased by 41% in the past decade to a current level of about 45,000 m^3/day, whereas the demand for gasoline has decreased by about 4.5%, and that for light fuel oil has decreased 53% in the same period. In the past 10 years Canada's demand for all petroleum products (and hence oil refined) has been reduced by 15% to a current level of about 228,000 m^3/day. Diesel for highway use now represents about 65% of the total diesel fuel demand in Canada: up substantially from the 44% level of 1975-6. Thus diesel fuel for highway use represents about 12% of Canada's total demand for petroleum products and all types of diesel for all uses about 18.2% of petroleum demand. While this is a modest percentage of the total petroleum demand, it is a critical part since diesel is a key fuel for industry.

The trends in diesel fuel demand indicate strong growth in the market for the highest quality (highway) diesel fuels at a time when refinery throughput and gasoline production have been reduced. At the same time as the demand ratio has changed, so has the quality of the crude oil to the refineries; a trend to increased use of synthetic crude derived from tar sands has occurred. Both the increased demand and the change in crude oil origin and quality will have the effects on diesel fuel described in the following sections 2.1.1 to 2.1.4.

2.1.1 Diesel Cost

The supply of diesel fuel produced from each barrel of oil processed will need to be increased: this necessitates new equipment and new modified processes resulting in higher costs for diesel fuel and allocation of fuel costs to diesel for the new capital recovery and added processing costs relative to other petroleum products (gasoline in surplus may not be able to absorb costs as before). The higher cost for diesel fuel can be noted already: the price of commercial diesel fuel has not been reduced significantly in recent months where lower oil prices have permitted corresponding reductions in the price of gasoline.

2.1.2 Highway Diesel Quality

The quality of diesel fuel available for highway use will continue to deteriorate. This is due to the use of synthetic crudes and heavy crudes which result in a reduction in the proportion of virgin distillates used to formulate diesel fuel and increased reliance on fractions from catalytic crackers (light cycle oil) and a deterioration in the quality of middle distillates, due to the incorporation of distillates form highly aromatic syncrude fractions. The major effect of these changes will be a more aromatic middle distillate pool which will have poorer ignition quality. This lower quality is manifested in vehicles by poor cold start characteristics (often starting with "blue smoke" emitted), reduced engine life, increased engine noise and increased levels of unwanted exhaust gas emissions (unburnt hydrocarbon, increased particulates and NOx). The quality will also be degraded by the diversion of low quality #2 heating fuel into the diesel fuel, since this outlet for lower quality distillate is shrinking.

2.1.3 Upgrading and Diesel Extension

The quality trends can be overcome by expensive hydrotreating of middle distillates and in part also by the addition of cetane improvers - the most cost-effective of which are organic nitrates, such as iso-octyl nitrate, used extensively in the present tests to improve the ignition quality of diesel-alcohol blends. The use of hydrogenation or ignition improvers increases the cost of diesel fuel substantially.

Diesel fuel ignition improvers unquestionably provide the lowest cost method of ignition quality improvement (as measured by the cetane number of the fuel) but the extent to which they may be used in North America is unknown, especially in the light of their added nitrogen content, part at least of which appears in the vehicle exhaust emissions as NOx. Reliance on hydrotreating to upgrade diesel fuel could increase diesel fuel costs by as much as 2¢/litre where high levels of syncrude are used as refinery feedstock: the cost of organic nitrates to upgrade the syncrude-rich 1990 diesel to current specifications is about 1¢/litre of product.

2.1.4 Long Term Concerns

Canada is still dependent on imported oil for 18-20% of its total oil requirements of about 294 million m^3/day. This, despite the fact that oil and oil product exports currently exceed the level of imports. However, these exports include heavy crude and asphalt. Canada's dependence on oil imports will increase in the future and particularly so if crude oil prices remain low, since the marginal cost of oil exploration, production and delivery from frontier (off-shore and Artic) sources is substantially higher than the cost of imports, as is the cost of incremental expansion of the syncrude plants. Low-cost Alberta-sourced conventional crude oil is rapidly being depleted. There is a strong incentive from fuel security of supply and long term cost perspectives to increase the use of natural gas in Canada as a transport fuel, either directly or in a converted form such a methanol.

These long term diesel and crude oil supply constraints and medium term future price considerations are national concerns, which prompted the present investigation of the use of methanol in highway diesel fuel. Another concern is with the compromises in engine life and efficiency that must be assumed by the transport industry in Canada when large volumes of syncrude are used in the production of diesel fuels which will lead to quality represented by the "1900 diesel" sample.

2.2 POLLUTION STANDARDS

Concern over vehicle emissions now encompasses those from diesel engines used in highway transport. Diesel engine manufacturers in the US and Europe and Japan (no diesels in the highway vehicle range are manufactured in Canada) are very active in the development of engines and post-combustion devices which will reduce the levels of hydrocarbon, NOx, CO, and particulates to meet the future stringent standards in heavy duty engines without undue sacrifice in fuel economy.

The present and future Canadian standards (US with Canadian adoption of the same standards) for heavy duty vehicles given in terms of grams per Brake Horsepower Hour (g/BHPH) are:

		Hydrocarbon	NOx	Particulates
Current:	Canada		HC+NOx=16	Smoke measurement(opacity)
	U.S.A.	1.3	10.7	Smoke measurement(opacity)
Future:	N. America			
	1988	1.3	6.0	0.6
	1991	1.3	5.0	0.25(trucks); 0.1(buses)

Two components of the strategies being pursued to meet these standards are relevant to the current investigation:

- the use of diesel fuel additives and substitutes to reduce emissions

- o the use of exhaust after-treatment trap/oxidizers to contain and then burn off particulates.

2.2.1 Fuel Change Strategy: Alcohol in Diesel

Two buses are under test in San Francisco in which methanol is being used as a bus fuel: one in a slightly modified 2-stroke DDA compression ignition engine, the other in a spark-ignition engine produced from a 4-stroke diesel engine (similar engines have been tested in Germany and New Zealand).

The compression ignition engine operated on methanol meets the 1991 Exhaust Emission Standard for Heavy Duty Engines (Trucks) but not yet for the bus particulates (0.1 g per BHPH) specification. The Canadian MILE program (Methanol In Large Engines Program) now initiated will provide more data on the use of methanol in a variety of bus and truck engines.

A state-of-the-art review by the US Department of Energy reviewed early work on diesel-alcohol fuel emulsions, including work by the Ontario Research Foundation on mechanically produced 20% methanol in diesel fuel emulsions, and US and European work on diesel-alcohol emulsions prepared with 3-3.5% volumes of fatty acid-derived surfactants.

In general (but see Section 3 with important exceptions), the effect of alcohol in diesel emulsions compared to the base diesel fuel was to:

- increase NOx
- increase unburned hydrocarbon
- decrease carbon monoxide at full load (no change at part load)
- decrease particulates (in step with the amount of alcohol used)
- energy efficiency remained essentially unchanged (allowing for the low heat of combustion of oxygenated fuels versus all hydrocarbon diesel fuel.)

However, the use of aqueous methanol in diesel emulsions and diesel-water emulsions appeared from other work to offer an opportunity to optimize fuel compositions and to take advantage of the known property of water injection (which reduces NOx emissions because of reduced peak temperatures) without unduly increasing particulates (another known property of water in diesel fuel). Again, the water-alcohol-diesel emulsion permits low cost addition of water-soluble salts which were expected to be as effective in reducing particulates and improving NOx as certain well-known diesel-soluble organic analogues such as barium naphthenate (for smoke reduction) and organic nitrates (for cetane improvement).

As discussed in Section 6, these expectations for the aqueous alcohol-diesel emulsions were realized. Work with methanol blends and water in gas turbines used for electric power generation has clearly demonstrated the ability of both methanol and water additions to reduce NOx emissions and the ability to operate these stationary engines with distillate fuels combusted in the presence of large proportions of water (up to 55% by weight of distillate) and methanol.

2.2.2 Equipment Change Strategy: Use of Oxidizing Particulate Traps

The control of particulate emissions from heavy duty engines is expected in the future to involve the use of particulate traps which can be regenerated intermittently by increasing the temperature of the trap and burning off the accumulated soot with air. The frequency and ease of the burn-off process will determine the economics of this particulate control strategy.

It is well known that the addition of alcohols to diesel fuels not only reduces the level of particulates but also changes their properties, as evidenced by the ratio of hexane* soluble to hexane insoluble (soot) particles. This was one particulate control expectation from the current diesel methanol blend investigation. Another was that the water-containing emulsions would provide a medium for the transport of heavy metal salts which might catalyze reactions in a manner similar to that shown by the corresponding diesel-soluble, more complex metallo-organic compounds, such as barium naphthenate for smoke

*Note: The bulk of existing literature refers to the use of hexane as the solvent, but the data is relevant to any light hydrocarbon technique. In the work reported in Sections 5.0 and 6.0 dichloromethane was used as a solvent.

reduction and lead, copper and manganese additives now being investigated by Ford, GM, Volkswagen and others (see reference section) as means to catalyze particulate combustion on regenerative particulate filters. In the present work only barium acetate was investigated: it did show a reduction in soot formation and total particulates. Further tests with inorganic salts of manganese and possibly other metals will show whether these can function as catalysts for filter regeneration, in addition to reducing soot formation at the fuel combustion step.

2.3 METHANOL USE

Canada has a production capacity of 1,800,000 tons of methanol per year with domestic demand in the region of 300,000 tons per year. Canadian export markets in the US and Japan are under pressure from new sources of methanol supply from Saudi Arabia and other gas-rich countries and the anticipated market for methanol as a gasoline additive has not yet materialized. Use of methanol in diesel fuel would permit extension of short diesel supplies by plentiful methanol. Furthermore, Canada's capacity for the production of methanol from natural gas is not limited by gas supplies, since over 35 years of proven natural gas supply to current domestic and US export markets is available and sales, not production, is the current problem of the gas industry. Canadian methanol producers with plants in Alberta and British Columbia receive gas at preferential rates but in the short term may not be able to supply methanol at costs competitive with those of diesel fuel if methanol is only used as a extender of diesel.

In the long term, as discussed above, the price of diesel fuel will rise with respect to crude oil and become more competitive. This will be added by any premium that can be charged for methanol-diesel fuel combinations if they can be demonstrated to be effective pollution abatement materials. The ability to blend water into the compositions and to replace expensive organic improvers with low-cost ammonium nitrate or other salts will enhance the competitiveness of the methanol used in the diesel formulation. Compositions based only on diesel-water emulsions have been evaluated in the present study and may be useful as diesel pollution and performance improvers but large-scale displacement of diesel fuel would require the addition of a combustible additive such as methanol (or ethanol in other locations). A further rationale for the current study is therefore to demonstrate a new use for methanol and means for reducing Canada's imports of crude oil through partial substitution of diesel fuel in new diesel fuel emulsions.

2.4 THE NEW EMULSION TECHNOLOGY

Under normally accepted vehicle operating conditions, methanol or ethanol are considered to be immiscible with diesel fuels. Thus arises the difficulty of incorporating alcohols as a portion of the diesel fuel supply.

One method to overcome this problem is to form an emulsion of the alcohol diesel system using chemical emulsifiers.

Hundreds of potential chemical emulsifiers have previously been screened by various researches, however, no stable and practical emulsions have been reported.

Dalco (diesel, alcohol coupler) is a new carbon, hydrogen oxygen based emulsifier which can emulsify a wide percentage of alcohol with diesel fuel.

The Dalco emulsion is an alcohol dispersed phase in a continuous phase of diesel fuel and is formed by mixing the Dalco with the diesel fuel and alcohol in a high shear mixing device. The emulsion may be handled and stored as a low flash point fuel and is miscible with diesel fuel in any proportion thus avoiding refueling problems. The viscosity is approximately that of normal diesel fuels and the emulsion is stable within diesel engine fuel systems.

The Dalco emulsion technology produces a stable and practical emulsion for use in a totally unmodified diesel engine.

3.0 PREVIOUS WORK ON DIESEL-ALCOHOL EMULSIONS

Six blends of 15-20% methanol in #1 diesel fuel were prepared using the Dalco copolymer emulsifier system and evaluated in a Perkins single cylinder test engine and the results compared with those achieved with three reference diesel fuels of varying cetane number (50.5; 45.0; 39.6CN). The confidential tests were reported by Perkins and made available by Erco Canada Ltd. to facilitate the current work. The conclusions were:

- The surfactant then available permitted the production of diesel-methanol 15 and 20% blends with short-term storage stability.

- The engine could be run satisfactorily using the 15-20% methanol blends but high variations in pressure rise with the cetane unimproved formulations required that the engine timing be retarded to avoid mechanical damage (diesel knock due to the low ignition quality of the fuels). The ignition quality (as measured by cetane number) was improved by the addition of 0.2-0.4% of an organic nitrate-type ignition improver. Dramatic reductions in exhaust smoke compared to diesel fuel were reported.

Similar tests were conducted by Perkins using the single cylinder engine with emulsions containing ethanol at the 15, 20 and 25% volume level in a Canadian #1 diesel fuel. The results were:

- Stable emulsions could be prepared using the copolymer emulsifier.

- No significant change in thermal efficiency occurred with ethanol emulsion compared to diesel fuel.

- A moderate fall in performance was observed with the emulsions due to change fuel delivery (higher viscosity of the emulsions) and reduced heat of combustion of the alcohol.

- The addition of ethanol to diesel increased the peak cylinder pressure and rates of pressure rise up to and exceeding the acceptable limits for the Perkins engine.

Ethanol use at the 20 and 25% was therefore rejected and the use of 15% ethanol not recommended in a 45 cetane (Canadian #1 specification) diesel fuel: 50 cetane (unavailable in Canada) was recommended for a 15% ethanol formulation or modification of the engine timing. The latter would have resulted in a high smoke emission level when the engine switched to diesel fuel alone. The formulation of cetane-improved diesel-ethanol blends was not attempted.

Further tests conducted in a typical naturally-aspirated tractor engine (6-in-line, 4-stroke, 6-litre direct injection) using emulsions with 15, 20 and 30% ethanol showed:

- The torque and power were reduced as the ethanol content increased but the decrease was not directly proportional to the heating value of the fuel: a 2% gain in energy efficiency was noted in the intermediate (1400 rpm) engine speed range.

- Increased but acceptable peak combustion pressure was observed and attributed to a combination of ignition delay and higher flame spread rate when combustion was initiated.

- Smoke and exhaust gas temperatures were reduced with ethanol content.

- NOx emissions were reduced considerably with 15 and 20% ethanol blends at lower speeds but not with the 20% blend. The reduction in NOx is an exception to previous reports.

- CO emissions were markedly reduced with increasing ethanol content. It was concluded that 20% ethanol blends could be used in an unmodified diesel engine.

Similar results were obtained with the same emulsions in a similar engine from another manufacturer (International Neuss).

Further tests in Australia with emulsions prepared from 15% methanol and ethanol (each containing 5 volume % of water) and a high cetane diesel fuel without cetane improver in an unmodified Ford 3000 engine led to the conclusion that the 15% alcohol fuels could be used without cetane improvers with (surprisingly) no loss in power experienced in comparison with the base diesel fuel, despite reduced heat content of the emulsions. Further, the maximum increase in peak cylinder pressure experience (with methanol 15% at 2000 rpm) was only 70% - considered by the Australian authors to be acceptable for durability with this particular engine.

In summary, previous work with Dalco-stabilized alcohol-diesel emulsions indicated that satisfactory engine performance could be achieved with 15% alcohol substitution level without ignition improvers and with gains made in emissions (NOx, particulates, frequently CO). Some surprising results were reported for thermal efficiency with 15% alcohol blends: unsurprising results at other levels.

Levels of diesel substitution above 15% appear to require cetane improvement to reduce the risk of diesel engine damage due to delayed ignition followed by fast burn of the diesel-alcohol mixture: a mild incidence of this combustion condition is probably the cause of the higher than diesel fuel thermal efficiency observed at lower alcohol concentrations.

The results reported for Dalco-stabilized diesel-alcohol emulsions are not entirely consistent and differ in some details from work reported on methanol and ethanol-diesel emulsions prepared using conventional surfactants and mechanically-prepared methanol-diesel blends. It is clear that differences in ignition quality that arise from the level of alcohol addition, the ignition quality of the diesel used and the use of ignition improving additives have a great influence on the combustion process which can be changed by optimization of the engine timing. The reduced level of particulate emission with alcohols is a consistent feature, as is reduced carbon monoxide emission at full load conditions.

Specific formulations with optimized engines appear to offer the prospect of unanticipated gains in the form of reduced levels of NOx emission and high thermal efficiency using 15% or less of alcohols by volume in the emulsions, and that these arise when a critical balance is achieved between ignition delay and fast fuel burning when ignition does occur.

The results of the present investigation of diesel-methanol and diesel-water emulsions prepared using the Dalco copolymer emulsifier extend knowledge on the relationships that exist between engine performance and fuel composition within the critical composition ranges where gains in thermal efficiency and improvements in engine exhaust emissions could be achieved.

4.0 FUEL CHARACTERIZATION

4.1 FUEL FORMULATION TECHNIQUES

The complete range of fuel formulations tested is listed in Table 1. The rationale for the particular formulations chosen was as follows:

- The initial range of fuels, reference numbers 1 to 7 used #1 Diesel fuel as the base fuel on the basis that this was a likely fuel for use in light to medium duty trucks used in cities. The range of formulations tested explored the effect of increasing methanol substitution.
- An exploration of the effect of ignition improver was carried out with fuels 8 to 11, continuing with Diesel #1 as the base fuel. Ignition improver quantities were chosen in an attempt to offset the decreasing ignition quality of the formulation as methanol content increased.
- The effects of DALCO and DALCO plus water were investigated using fuels 12, 13 and the opportunity of using aqueous soluble ignition improvers and smoke suppressants examined using fuels 15 and 16 without methanol addition.
- The combined effects of emulsions containing methanol and substantial quantities of water were tested using blends 17 and 23.

- The effects of using other than Diesel #1 as a base fuel were explored in blends 18, 19, 20 and 21 using Diesel #2 as the base and adding progressively increasing amounts of methanol. Fuel 22 was a 1990 quality fuel prepared by NRC. Baseline tests without additive were carried out with this fuel. No blends were successfully achieved by the end of testing using 1990 base fuel.

In addition to the above discussed blends, small pilot quantities of other formulations using water soluble oxygenators such as hydrogen peroxide were prepared but not fully tested, on the grounds of physical and chemical instability.

4.2 ANALYSIS OF FORMULATED AND BASE FUELS

4.2.1 Stability

fuel samples were procured at the start of testing of each specific fuel blend. It should be noted that previous to sampling, the fuel drum (forty-five gallons) was well shaken to provide a well-mixed sample. A considerable effort was made to ensure that the samples were obtained from the middle of the test drum, and upon being stored in air tight glass jars, they were not handled or shaken.

A selected group of fuel blends, as shown in Figures 2 - 8, were photographed through the duration of the test program as a representative cross-section of all the fuel blends. These photographs are listed in

FUEL REF. NO.	FUEL DESCRIPTION				
	BASE FUEL	% METHANOL	% WATER	%DALCO	OTHER
1	D#1	-	-	-	-
2	D#1	5	-	1.17	-
3	D#1	10	-	2.33	-
4	D#1	15	-	3.5	-
5	D#1	20	-	4.6	-
6	D#1	25	-	5.8	-
7	D#1	30	-	7.0	-
8	D#1	15	-	3.5	0.1 DII*
9	D#1	25	-	5.8	0.2 DII
10	D#1	30	-	7.0	0.2 DII
11	D#1	30	-	7.0	0.4 DII
12	D#1	-	5	2.5	0.15 DII
13	D#1	-	-	2.5	-
14	D#1	-	5	2.5	-
15	D#1	-	5.5	2.75	Ammonium Nitrate
16	D#1	-	5	2.5	Barium Acetate
17	D#1	7.5	7.5	3.0	0.2 DII
18	D#2	-	-	-	-
19	D#2	15	-	3.5	-
20	D#2	15	-	3.5	0.15 DII
21	D#2	20	-	3.5	0.2 DII
22	1990	-	-	-	-
23	D#1	15	2.5	2.35	0.15 DII

*Note: DII = Diesel Ignition Improver (Ethyl Corp.)

TABLE 1: FUEL FORMULATIONS

chronological order to visually distinguish various stages of phase separation in the fuels.

In Figures 2 - 6, the amount of phase separation is more noticeable in the fuel blends with lower percentages of methanol by volume. By November 19, 1985, after only 41 days of storage, the #1 diesel + 5% MeOH blend is noticeably phase separated with a distinct "powder" layer at the bottom of the sample. In Figure 5, the blends are noticeably less separated as methanol content by volume increases. This observation is further developed in Figures 6 and 7 with the introduction of a ignition improver in the fuel blends. By observing Figure 7, where most samples have been stored for at least 4 months, it is evident that the blends with high methanol content by volume, ignition improver, and DALCO, phase separate at a slower rate than straight diesel-methanol blends with DALCO. The first five fuels in Figure 7 contain no ignition improver and all appear to have fully phase separated. Figure 8 is a photograph of a different grouping of fuels which emphasize the increased phase separation effect water has on the diesel-methanol emulsions.

It should be noted that during the engine testing portion of the program, that direct fuel supply was never stored for more than a few weeks at a time. For all but one fuel (#1 D + 15% MeOH + 2.5% H_2O + 0.15% DII), starting and running for extended periods of time was not a problem.

FIGURE 2: FUEL SAMPLES AFTER 21 DAYS AT ROOM TEMPERATURE

FIGURE 3: FUEL SAMPLES ON NOVEMBER 5, 1985 AT ROOM TEMPERATURE

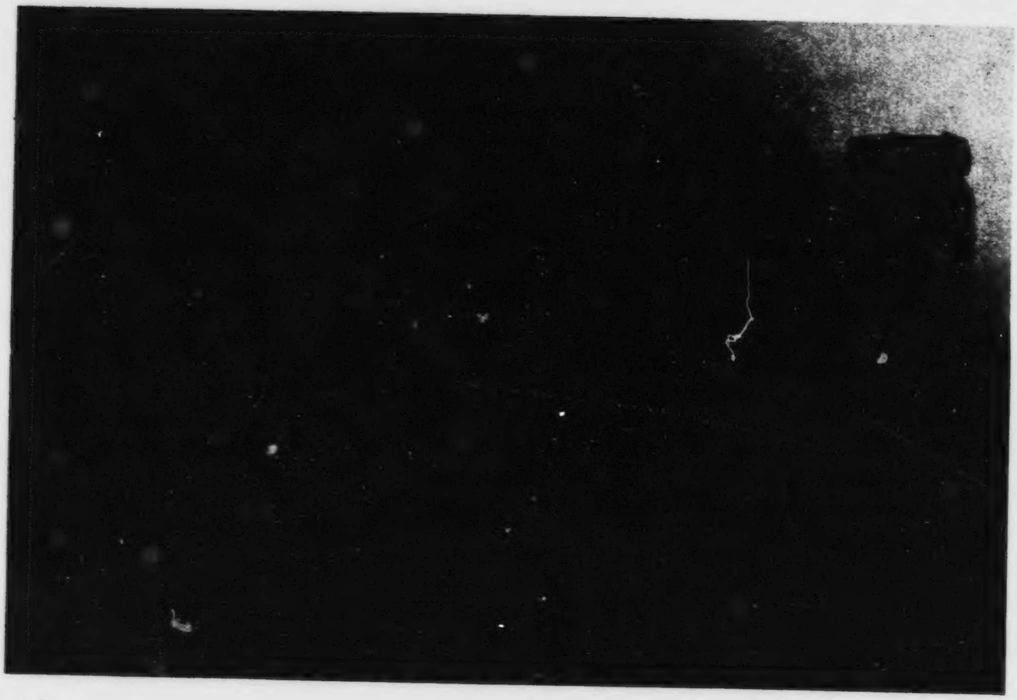

FIGURE 4: FUEL SAMPLES ON NOVEMBER 12, 1985 AT ROOM TEMPERATURE

FIGURE 5: FUEL SAMPLES ON NOVEMBER 19, 1985 AT ROOM TEMPERATURE

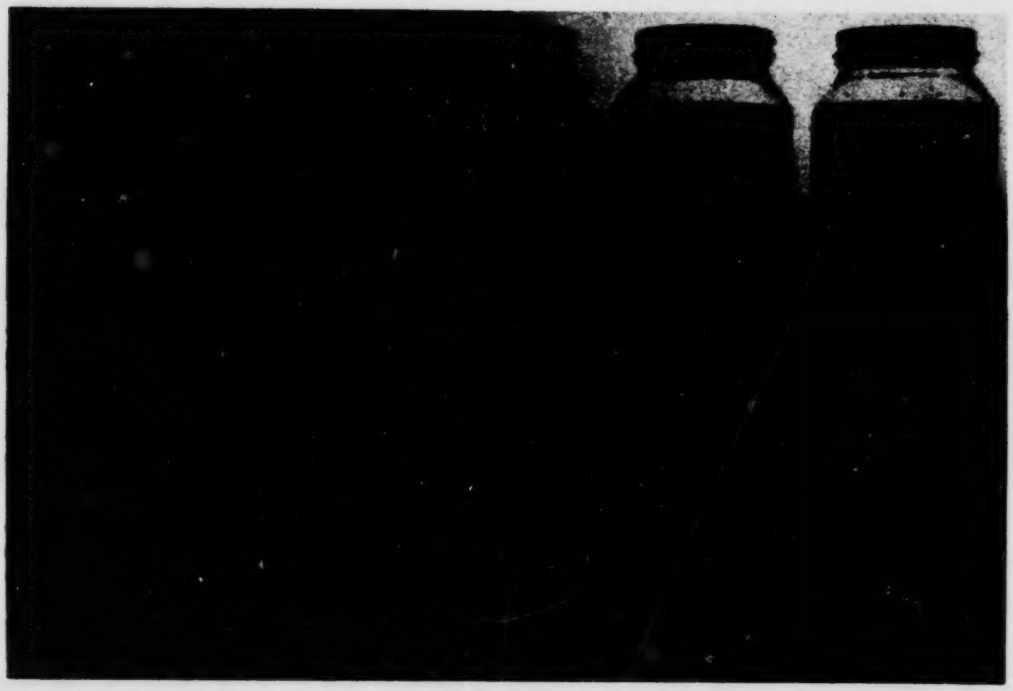

FIGURE 6: FUEL SAMPLES ON NOVEMBER 19, 1985 AT ROOM TEMPERATURE

FIGURE 7: FUEL SAMPLES ON MARCH 26, 1985 AT ROOM TEMPERATURE

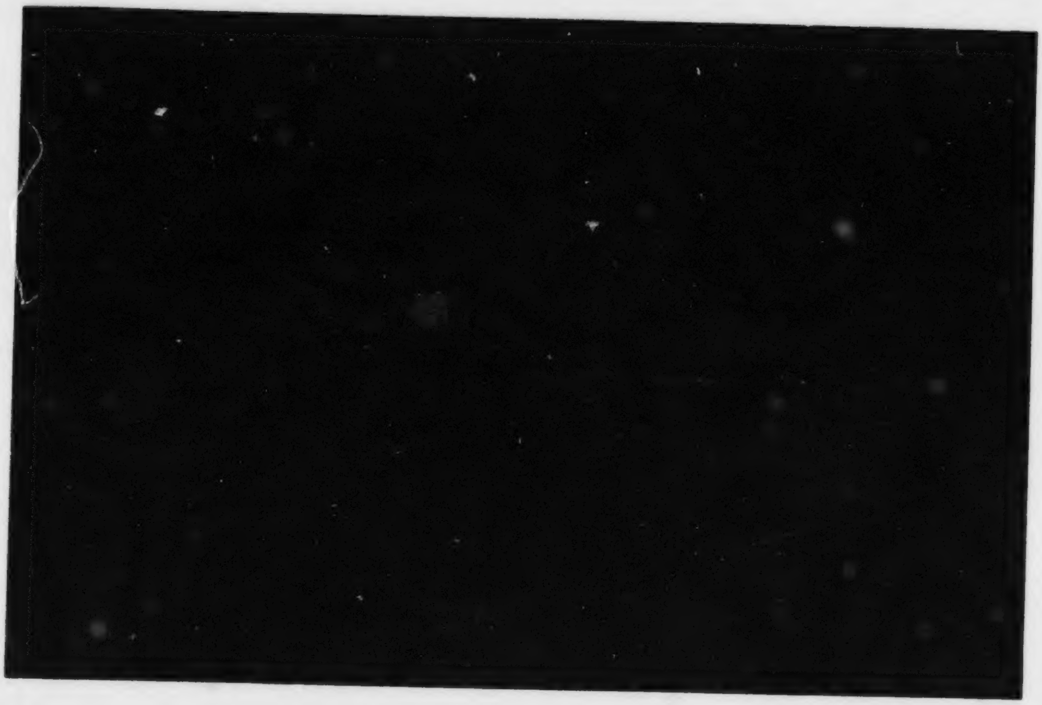

FIGURE 8: OTHER SELECTED FUEL SAMPLES ON MARCH 26, 1985
AT ROOM TEMPERATURE

4.2.2 Viscosity

The diesel-methanol emulsion fuels were submitted to ORF's lubrication lab for determination of viscosity. The experimental procedure, of necessity, followed a modified version of ASTM D445. As the temperature at which the determination took place, 25°C, was non-standard, the usual precision in control of temperature was not possible. Nevertheless, precautions were taken to avoid undue fluctuation in temperature throughout the determination. The results are listed in Table 2.

4.2.3 Combustion Related Properties

Combustion related properties including cetane No., heat of combustion and carbon/hydrogen ratio were investigated by the NRC Fuels and Lubricants Laboratory and the Laboratories of CANMET. The data is summarized in Table 3.

Ref. No.	Sample	Viscosity*
8	15% MeOH + .1% DII NG 91-85 Nov. 12	4.4
9	25% MeOH + 0.2% DII Nov. 13	8.7
10	30% MeOH + 0.2% DII W693-85 Nov. 6/85	11.3
11	30% MeOH WG94-85 + 0.4% II Nov. 12/85	11.4
3	10% MeOH WG87-85 Nov. 5/85	3.4
2	5% MeOH WG86-89 Nov. 5/85	emulsion was broken
4	15% MeOH WG88-85 Nov. 5/85	3.9
5	20% MeOH WG87-85 Nov. 4/85	5.0
6	25% MeOH WG90-85 Nov. 4/85	6.5
1	Neat Diesel Fuel (#1)	2.2

* Note: As the temperature of the sample during measurement could not be as accurately controlled as is usual for D445, the precision of result is given only to the first decimal place.

TABLE 2: VISCOSITY OF DIESEL FUEL/METHANOL EMULSIONS AT 25°C

FUEL REF. NO.	COMPOSITION					VISCOSITY cSt	CETANE NO.		CETANE NO.		GROSS HEAT OF COMBUSTION BTU/1b	ELEMENTAL COMPOSITIONS % WEIGHT			
	BASE FUEL	% METHANOL	% WATER	% DALCO	OTHER		D613	CCR	D613	CCR		CARBON	HYDROGEN	OXYGEN	SULPHUR
1	D#1	-	-	-	-	2.2	42.7	44.5	-	-	19735	86.4	13.5	0.00	0.22
2	D#1	5	-	1.17	-	-	41.7	44.1	-1.0	-0.4	19420	85.9	13.2	0.81	-
3	D#1	10	-	2.33	-	3.4	40.7	41.1	-2.0	-3.4	19004	84.0	13.2	2.28	-
4	D#1	15	-	3.5	-	3.9	-	37.0	-	-7.5	18579	82.3	13.4	4.25	-
5	D#1	20	-	4.6	-	5.0	-	31.0	-	-13.5	18220	80.2	13.2	8.34	-
6	D#1	25	-	5.8	-	6.5	-	27.0	-	-17.5	17539	78.3	13.2	8.34	-
7	D#1	30	-	7.0	-	-	-	30	-	-14.5	16881	75.3	13.2	11.30	-
8	D#1	15	-	3.5	0.1 DII	4.4	-	40.8	-	-3.7	18427	82.1	13.2	4.40	-
9	D#1	25	-	5.8	0.2 DII	8.7	-	33.2	-	-11.3	17313	76.7	13.0	10.3	-
10	D#1	30	-	7.0	0.2 DII	11.3	-	28.2[1]	-	-16.3	16673	74.0	13.0	13.0	-
11	D#1	30	-	7.0	0.4 DII	11.4	-	31.9	-	-12.6	16752	73.8	12.9	13.5	-
12	D#1	-	5	2.5	0.15 DII	-	48.2	50.0[1]	+5.5	+5.5		84.97	13.59		-
13	D#1	-	-	2.5	-	-	-	40.1	-	-4.4		86.16	14.06		-
14	D#1	-	5	2.5	-	-					19091	84.1	13.5	1.99	-
15	D#1	-	5.5	2.75	Amm. Nit.	-						80.94	13.09		-
16	D#1	-	5	2.5	Bar. Ac.	-						86.30	14.10		-
17	D#1	7.5	7.5	3.0	0.2 DII	-						76.92[3]	14.11[3]		-
18	D#2	-	-	-	-	-	-	44.4	-	-	19705	86.4	13.6	0.00	0.19
19	D#2	15	-	3.5	-	-	-	35.0	-	-9.4	18604	82.4	13.3	3.76	-
20	D#2	15	-	3.5	0.15 DII	-	-	39.8	-	-4.6	18529	81.1	13.3	5.30	-
21	D#2	20	-	3.5	0.2 DII	-	-	34.7[1]	-	-9.7	17896	78.7	13.3	7.61	-
22	1990	-	-	-	-	-	-	33.4	-	-	19054	87.6	11.8	0.00	0.72
23	D#1	15	2.5	2.35	0.15 DII	-					17826	78.3	13.1	8.37	-

Note 1: Results Approximate Due To Erratic Engine Operation

Note 2: Methanol Tested Alone 9,711 BTU/1b Gross Heating Value

Note 3: Phase Seperation In Test Sample

TABLE 3: SUMMARY OF FUEL PHYSICAL DATA[2]

5.0 TEST EQUIPMENT AND METHODOLOGY

5.1 TEST METHODOLOGY

A test methodology was designed to test and evaluate all fuel formulations including a baseline set of tests on neat Diesel (#1). Testing of each fuel formulation included:

i) A Torque-Power Curve at rated loading;

ii) A Combustion Analysis utilizing the Norland DMX 3001 data acquisition system on the Torque-Power Curve and five selected load/speed settings. These load/speed settings outlined an engine map consisting of testing at:

  a) 2200 rpm/max. torque (rated);
  b) 1600 rpm/max. torque (rated);
  c) 1800 rpm/150 [ft. lbs.];
  d) 1400 rpm/50 [ft. lbs.];
  e) and idle condition/NO LOAD:

  each of these test points required approximately one hour for stabilization and data collection.

iii) A complete emission analysis for the five load/speed settings including gaseous emissions (CO, CO_2, THC, NO_x) and particulates (soluble and insoluble fraction).

The engine was operated on baseline diesel (#1 and #2) and on specified blends to determine the following parameters:

fuel consumption
torque and power output
peak cylinder pressure
maximum rate of pressure rise
ignition delay.

During each test run, these engine parameters and emissions were monitored for comparison with the baseline fuels. Other fuel formulation characteristics such as idle quality and engine run quality (smoothness) were also identified from each test. A total of 23 different fuel formulations were utilized in engine and fuel evaluation tests (See Table 1).

5.2 ENGINE SELECTION AND PREPARATION

The engine used for this Diesel-Alcohol Emulsion Program was the 4BT 3.9 Cummins Diesel. Technical details are given in Table 4.

This engine is a joint development between Cummins Engine Company and Case (U.S.A.) and represents state-of-the-art diesel engine technology in that it incorporates:

i) Direct Injection with bowl-in-piston type combustion chamber and flat head (two-valve head); multi-hole injection nozzle;

ii) Turbocharging, utilizing exhaust energy for higher mean effective pressures and improved thermodynamics;

iii) high efficiency;

iv) injection pump with high pressure injection lines to individual injectors (American BOSCH distributor type injection pump).

Most diesel engines manufactured today in North America for the automotive industry employ direct injection (bowl-in-piston type combustion chamber), turbocharging and a central distributor or in-line type injection pump with high pressure injection lines to individual injectors. The Cummins PT fuel system (as used on the NTC and the F series engines) is an exception and has been demonstrated not to be suitable for methanol/diesel emulsions (boiling of methanol in the injectors). The Cummins B-series engine, however, is typical of most other diesel engines.

The direct injection combustion chamber is a requirement for an engine to be used in this study. Pre-chamber engines (or IDI - indirect injection) are less sensitive towards cetane number, injection timing and ignition delay and would not provide the data for subsequent marketing. The DI engine, on the other hand, is very sensitive to optimum timing and fuel quality. Since the presence of methanol does affect the cetane number, ignition delay and rate of pressure arise (as observed in previous studies at

ORF), the D.I. chamber as present in the Cummins engine, will be an excellent tool for evaluation of different blends.

Distributor type pumps seems to be more susceptible to failure at the presence of methanol or ethanol compared to the in-line type pump, since they rely on the fuel for lubrication of all moving parts. Although the program does not include a durability aspect of the injection pump, possible early failure due to methanol may be identified.

After arriving at ORF, the engine was immediately prepared for testing utilizing standard combustion and emissions analysis set-up procedures. This will be discussed in detail in the following section.

5.3 TEST CELL SET-UP AND INSTRUMENTATION

The Cummins 4BT 3.9L diesel engine was instrumented, set-up on an engine stand in Test Cell #1, and connected via a driveshaft to a steady state Eatons Dynamatic Eddy Current Absorption Dynanometer, as shown in Figure 9. Engine speed was controlled by a Barber Coleman actuator, which was connected directly to the throttle. This test bed set-up utilized a standard water-cooling tower and high volume exhaust ventilation for maintaining engine cooling requirements. The engine's observed torque and speed were controlled and displayed on a control console as depicted in Figure 10. Various pressures and temperatures were monitored on this control panel. These included:

ITEM	DESCRIPTION
Configuration	4-cylinder, in-line
Displacement	240 CID (3.9 L)
Bore	4.02" (102.1 mm)
Stroke	4.72" (120 mm)
Power	105 HP @ 2500 RPM
Torque Max	260 ft/lb @ 1700 RPM
Intake System	Turbocharged
Fuel System	Distributor Type Injection Pump (American BOSCH)
Injector	Pintle needle type Injectors
Combustion Chamber	Direct Injection, with bowl-in piston type configuration.

TABLE 4: SPECIFICATIONS OF 4BT MODEL CUMMINS ENGINE ("B SERIES" ENGINE)

FIGURE 9: CUMMINS ENGINE SET-UP AND INSTRUMENTATION

a) Temperatures

- i) cylinder exhaust (for each cylinder)
- ii) air intake
- iii) air box temperature after the turbocharger
- iv) air temperature after turbocharger
- v) coolant temperature in
- vi) coolant temperature out
- vii) oil temperature
- viii) fuel temperature in
- ix) engine room temperature

b) Pressures

- i) oil
- ii) fuel
- iii) air intake
- iv) exhaust
- v) air box

A hole was machined through the cylinder head in the No. 1 cylinder to incorporate an AVL water cooled pressure transducer. This signal was passed through an AVL amplifier to be stored and analyzed by the Norland 3001 DMX data acquisition system (see Figure 10). The trigger pulses for sampling initiation on the Norland, along with sampling rate pulses, were generated by a Datametrics Tru-Mite encoder connected to the crankshaft. The shaft encoder set-up is shown in Figure 11. A Wolfe injection needle lift sensor (as shown in Figure 12) was utilized on the #1 cylinder injector. This signal was also amplified and stored at the same combustion pressure sampling rate in the Norland data acquisition system.

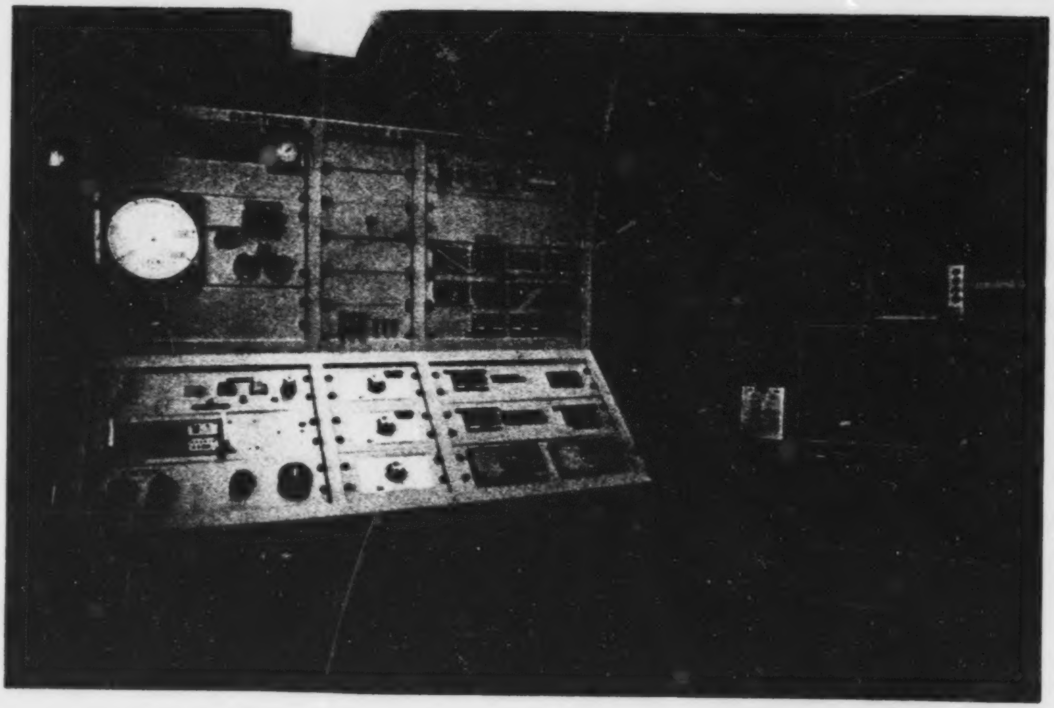

FIGURE 10: OPERATOR'S CONSOLE AND NORLAND DATA ACQUISITION SYSTEM

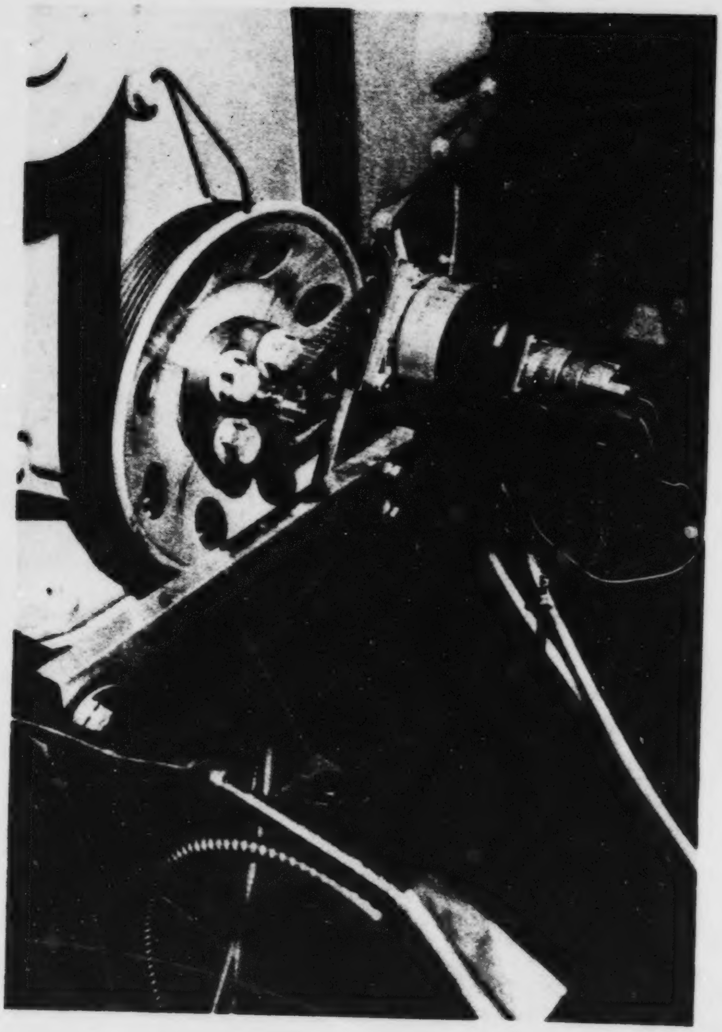

FIGURE 11: SHAFT ENCODER MOUNTING

FIGURE 12: NEEDLE LIFT SENSOR

Emissions analysis equipment included the Beckman gaseous emission bench, as shown in Figure 13. The specific analyzers to measure each component of gaseous emissions are well outlined in the flow diagram in Figure 14. Total particulate analysis was completed utilizing a dilution tunnel sampling system, as shown in Figure 15. These particulate filters, obtained from the dilution tunnel, were further broken down into soluble and insoluble fractions by chemical processing.

Calibration of the equipment was performed on a regular basis to ensure accuracy of data. Detailed calibration activities for various instruments are given in Table 5.

5.4 DATA REDUCTION TECHNIQUES

5.4.1 Combustion Chamber Pressure Traces

The pressure in the combustion chamber was recorded with a pressure transducer and a high speed data acquisition system (Section 5.3), which are critical components in analyzing the combusion processes of a particular fuel and the possible effects on the engine hardware.

An example of a combustion chamber and fuel injection pressure trace is shown in Figure 16. During the compression stroke, the air gets compressed and heated up, indicated by the rising pressure. Fuel is injected as indicated by the rapid rise of the injection trace. The injected fuel mixes with the hot air and compression ignition takes place. The

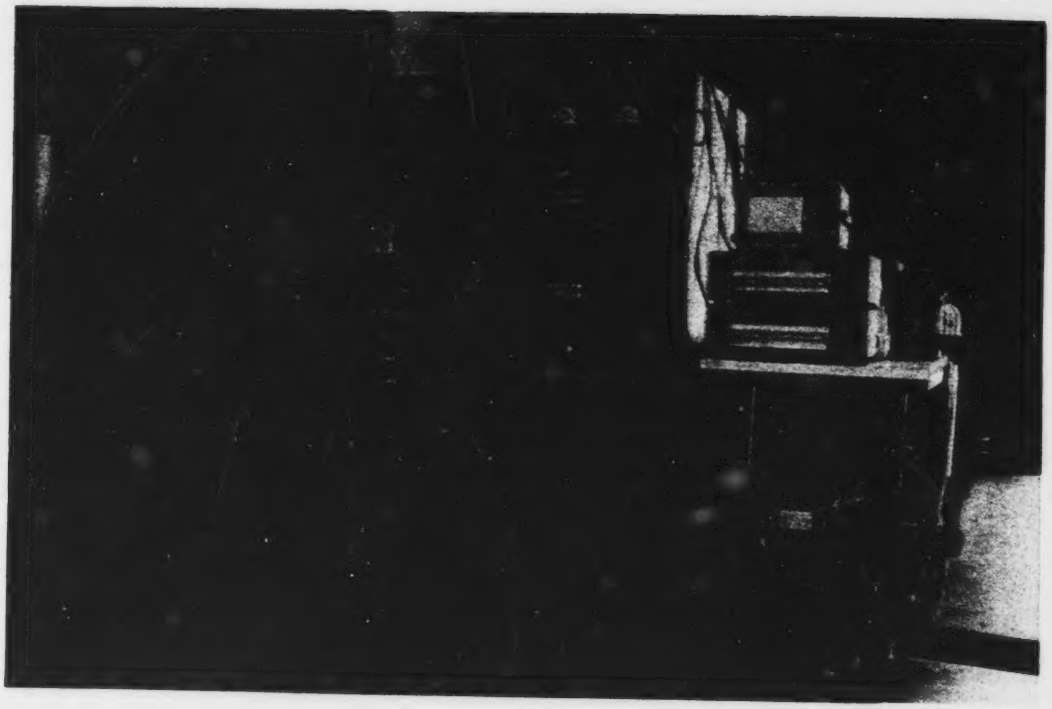

FIGURE 13: BECKMAN GASEOUS EMISSION BENCH SET-UP

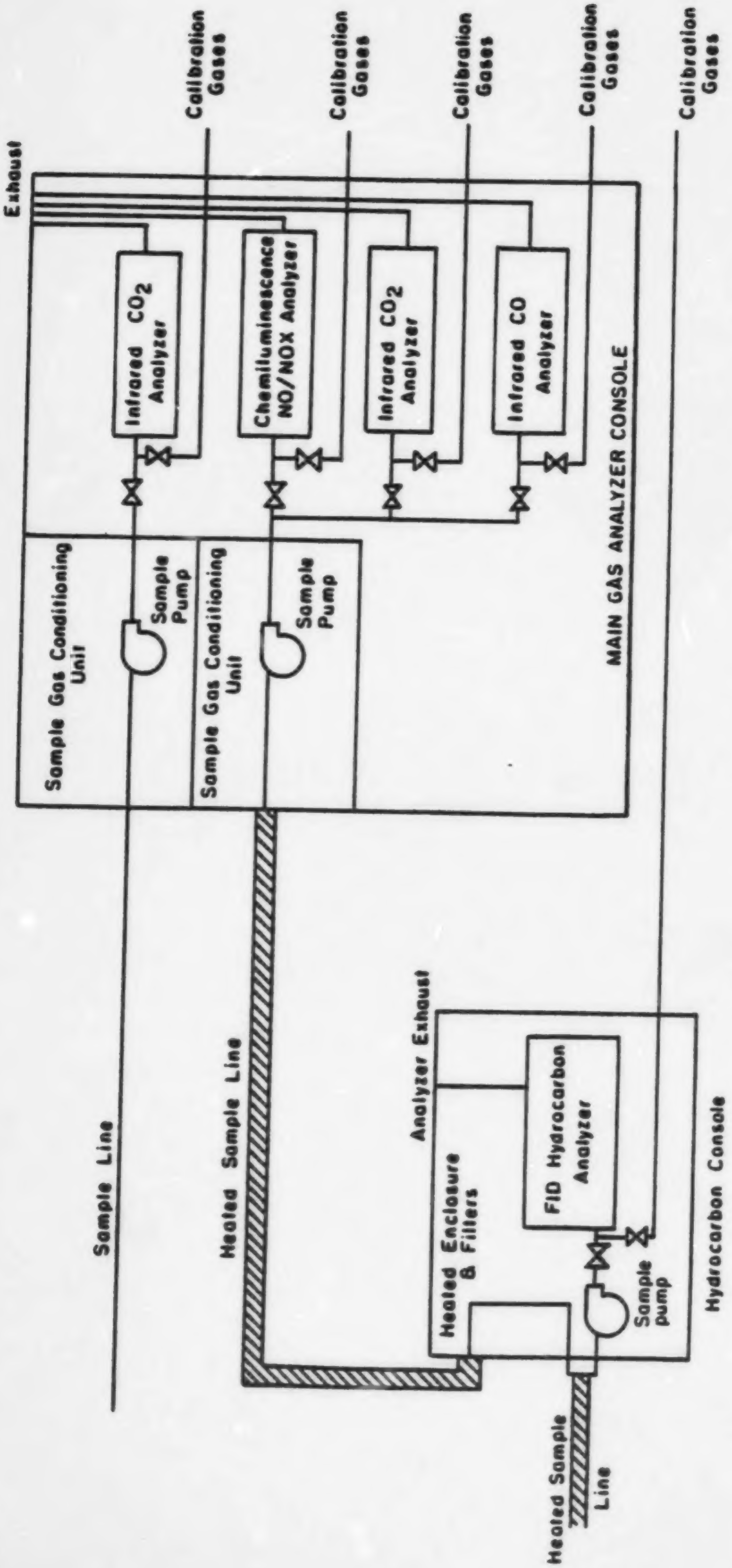
Calibration Gases
Calibration Gases
Calibration Gases
Calibration Gases
Calibration Gases
Exhaust
Infrared CO_2 Analyzer
Chemiluminescence NO/NOX Analyzer
Infrared CO_2 Analyzer
Infrared CO Analyzer
Sample Gas Conditioning Unit
Sample Pump
Sample Gas Conditioning Unit
Sample Pump
MAIN GAS ANALYZER CONSOLE
Sample Line
Heated Sample Line
Analyzer Exhaust
Heated Enclosure & Filters
FID Hydrocarbon Analyzer
Sample pump
Hydrocarbon Console
Heated Sample Line

FIGURE 14: FLOW DIAGRAM FOR EXHAUST GAS SAMPLING

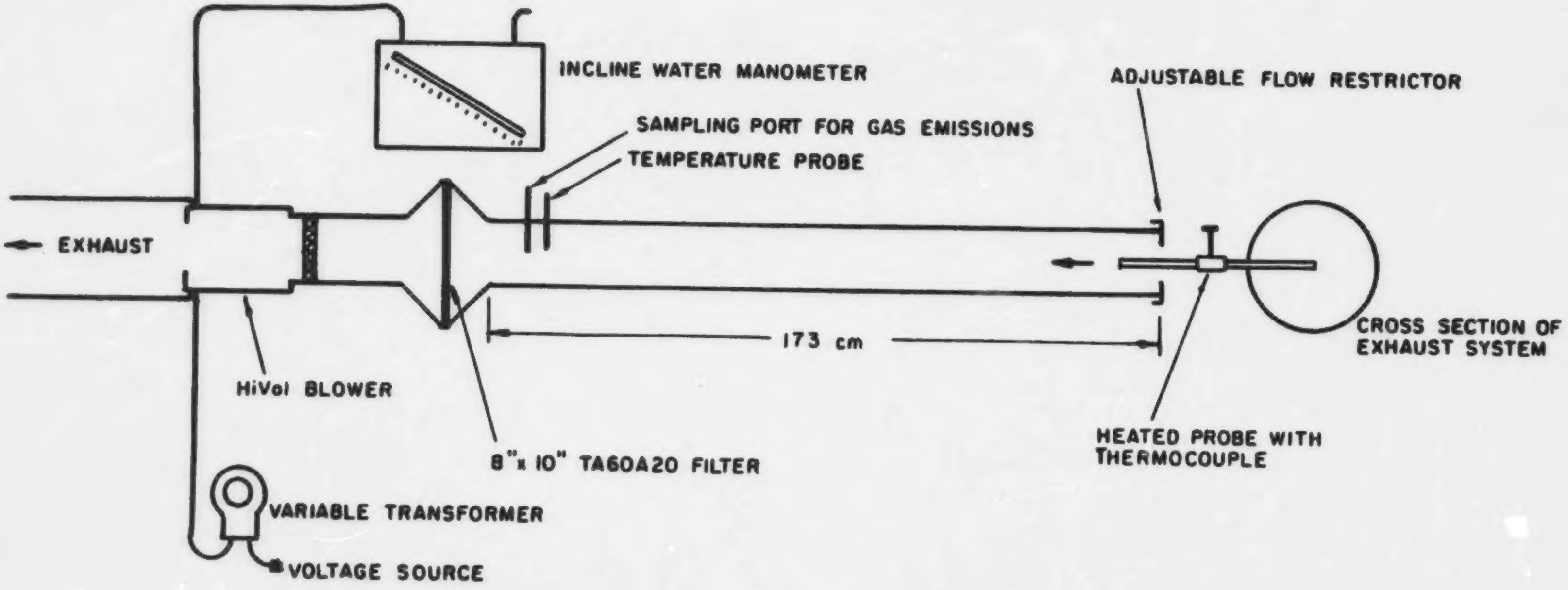
INCLINE WATER MANOMETER
ADJUSTABLE FLOW RESTRICTOR
SAMPLING PORT FOR GAS EMISSIONS
TEMPERATURE PROBE
EXHAUST
173 cm
CROSS SECTION OF EXHAUST SYSTEM
HiVol BLOWER
HEATED PROBE WITH THERMOCOUPLE
8" x 10" TA60A20 FILTER
VARIABLE TRANSFORMER
VOLTAGE SOURCE

FIGURE 15: DILUTION TUNNEL SAMPLING SYSTEM SCHEMATIC

Instrument/Equipment	Calibration Activity	Time
Load cell, dynamometer	Static calibration, using dead weights	Monthly
Dynamometer speed	Stroboscope	Monthly
Thermocouples	Hot oil at reference temperature	Beginning of project
Pressure gauges	Manufacturer	
AVL cylinder Pressure	Dead weight tester .	Bi-monthly
Emissions Bench	Calibration and span-gases	Daily

TABLE 5: CALIBRATION ACTIVITIES

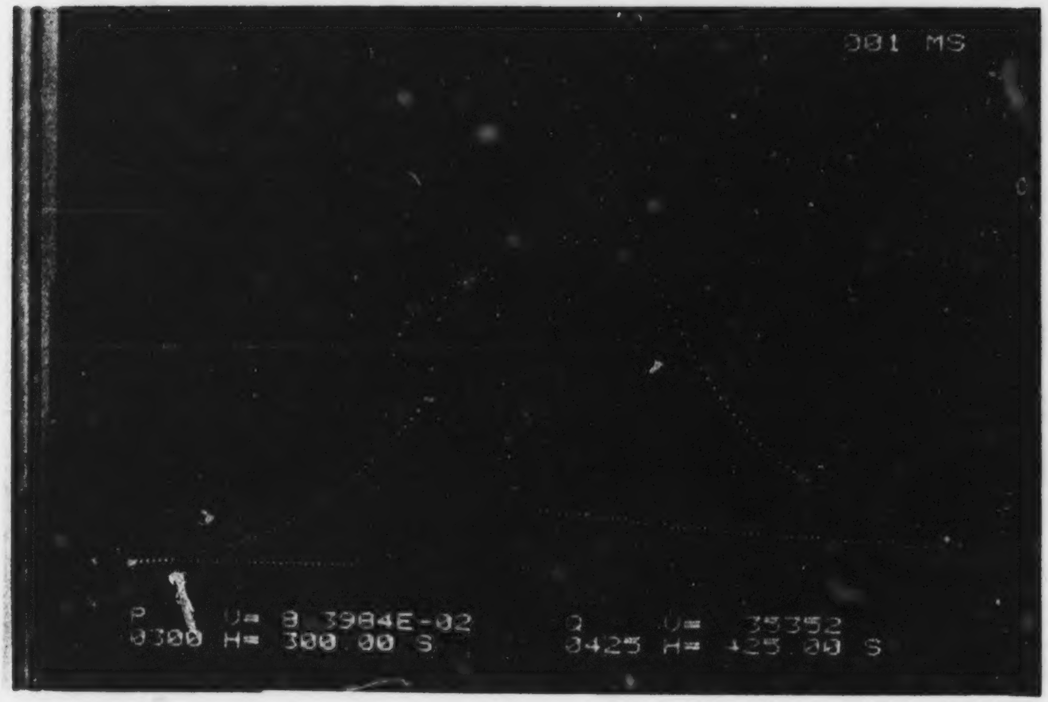

FIGURE 16: EXAMPLE OF COMBUSTION PRESSURE AND FUEL INJECTION TRACE FOR 1990 DIESEL AT 1600 RPM @ RATED LOAD

TOP CURVE: COMBUSTION PRESSURE TRACE
BOTTOM CURVE: FUEL INJECTOR LIFT TRACE

heat release results in a sharp pressure rise in the combustion chamber, which peaks shortly after the piston passes TDC (Top Dead Centre) and decreases as the hot gases are expanded on the downward moving piston. Figure 17 shows a schematic of this trace and its interpretation. The crank angle degrees between beginning of injection and greatest rate of pressure rise, P_{max}, are called ignition delay. The crank angle degrees between P_{max} occurrence and maximum or peak pressure (P_{max}), are an indication of the combustion duration. Although a heat release model would provide more details about the combustion process, for a comparative study, this analysis was found to be very satisfactory. Since each point in the pressure and injection diagram represents one crank angle degree, the interpretation of data was straight forward by moving cursors along the traces.

An example of a combustion and injection trace at low load is shown in Figure 18. The injection trace is very small, indicating a small quantity of fuel, as well as the resulting combustion chamber pressure.

The rate of pressure rise, P_{max}, peak pressure, and their occurrence, determine the structural strength of the engine. Any change in these parameters had to be monitored very carefully in the analysis of the data.

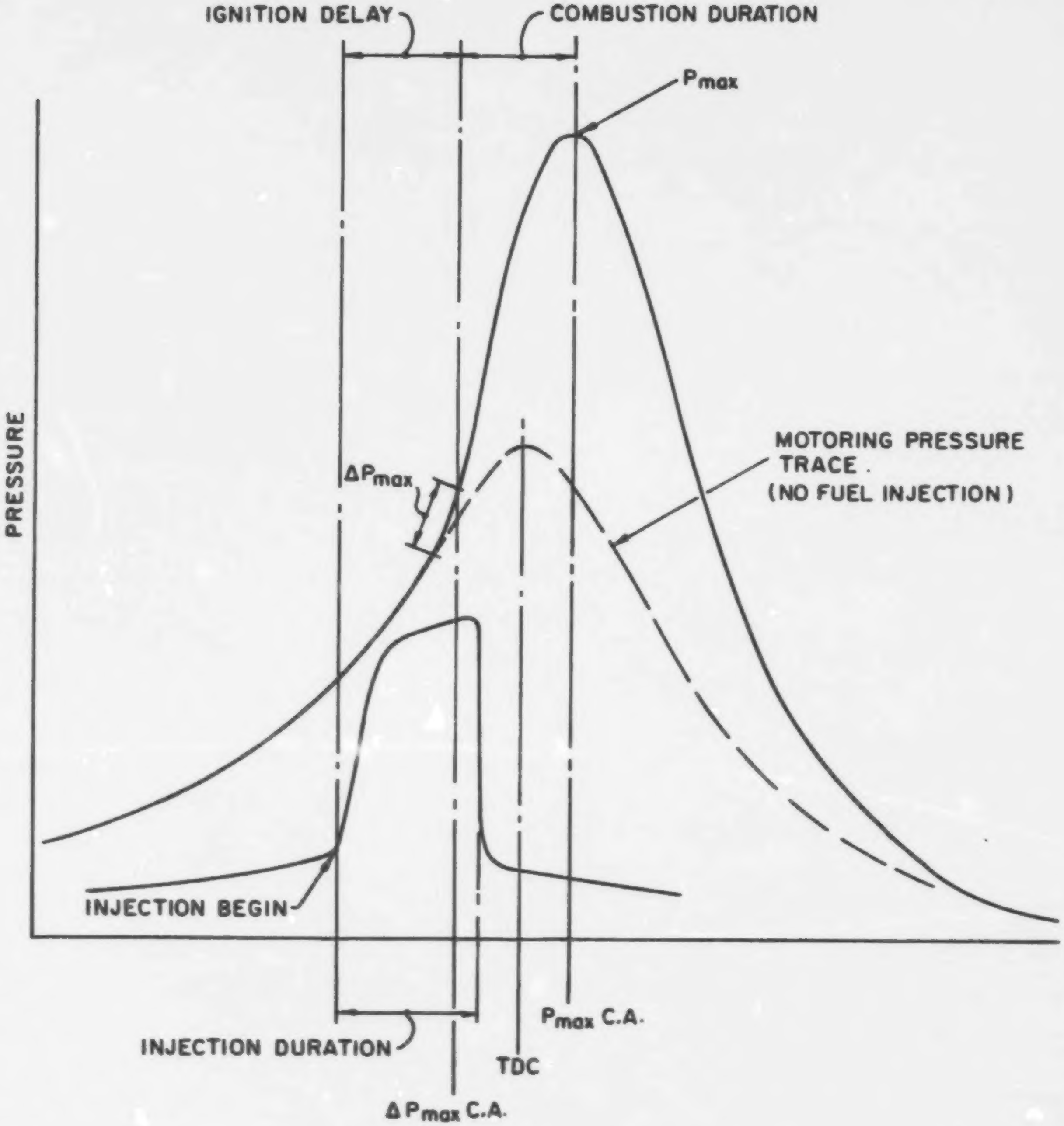
IGNITION DELAY
COMBUSTION DURATION
Pmax
PRESSURE
MOTORING PRESSURE TRACE. (NO FUEL INJECTION)
ΔPmax
INJECTION BEGIN
INJECTION DURATION
Pmax C.A.
TDC
ΔPmax C.A.

FIGURE 17: SCHEMATIC OF COMBUSTION AND INJECTION PRESSURE TRACE AND ITS INTERPRETATION

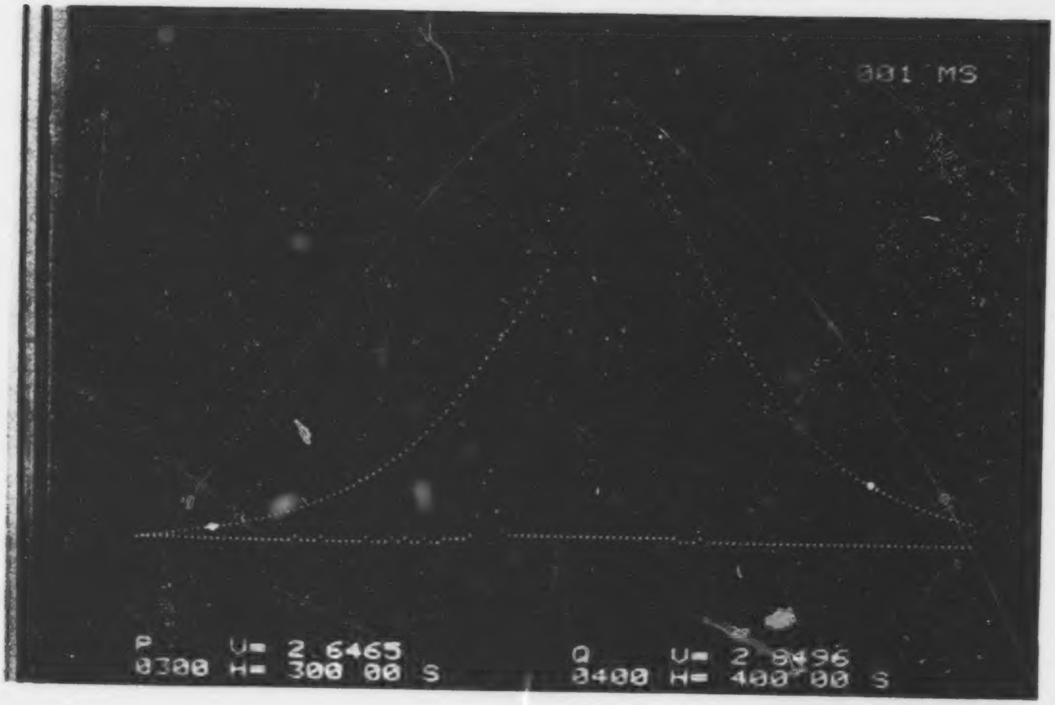

FIGURE 18: EXAMPLE OF COMBUSTION PRESSURE AND FUEL INJECTION TRACE FOR 1990 DIESEL AT IDLE CONDITON

TOP CURVE: COMBUSTION PRESSURE TRACE
BOTTOM CURVE: FUEL INJECTOR LIFT TRACE

5.4.2 Gaseous Emission Test Procedures

Gaseous emissions were determined for each of the test fuel blends over the various engine settings of the test schedule outlined in Section 5.1. At each of the test points, an average ppm measurement was recorded for carbon monoxide (CO), carbon dioxide (CO_2), and particulates.

Sampling was conducted through sample ports located in the engine's exhaust system. Exhaust gases were sampled through two heated filters (190°C) in a THC analyzer, (Beckman Model 402). The balance of the sample was directed through a second series of heated filters (190°C) for particulate removal, allowed to cool and passed through a Hannkinson dryer for moisture removal.

The conditioned sample was delivered, under a controlled flowrate, to a CO_2 analyzer (Beckman Model 864), NO/NO_x analyzer (Beckman Model 951A) and a CO analyzer (Beckman Model 867). Dilute CO_2 values were measured by a CO_2 analyzer (Horiba Model A1A21) after a separate sample line directed the sample gas through a second conditioning unit.

Figures 13 and 14 display the gaseous emissions sampling system.

All analyzer outputs were recorded and averaged utilizing a Hewlett-Packard 1000 data acquisition system. Final data calculations, tables and graphs were achieved through the use of an IBM personal computer in conjunction with a Lotus II software package.

5.4.3 Particulate Emission Test Procedure

Particulate sampling was conducted by diverting a portion of the engine exhaust through a heated probe into a dilution tube (See Figure 15). A calibrated high volume sampler was used as a primary air mover. The engine exhaust gases mix with ambient air before being passed through a pre-weighed 8" x 10" teflon coated glass fibre filter (T60A20). Dilution ratios were achieved by controlling the sample blower speed with a variable power source or by varying the ambient air intake.

After the test was completed, the individual filters were allowed to condition before a final total weight was determined. The filters were then extracted for eight hours with dichloromethane to remove the soluble portion of the particulates. The filter was then conditioned and re-weighed to determine the insoluble portion of the sample. The extract was retained for possible future analysis.

5.5 TEST RESULTS

A total of 23 fuel samples were tested. The identifying reference number of the specific fuel blends and their composition are outlined in Table 1. Performance and combustion analysis results for each fuel at rated load/speed settings are shown in Appendix A in Figures A1 to A92. This data is averaged and summarized in Table 6 to 13 and Figures 19 to 24.

FUEL	$\overline{P}$ max	$\overline{P}_{max}$ vs. Baseline P_{max}		$\Delta\overline{P}_{max}$	$\overline{\Delta P}_{max}$ ←(Baseline) vs. $\Delta\overline{P}_{max}$		$\overline{HP}$	$\overline{Hp}$ vs. Baseline $\overline{HP}$	
	(kPa)	Diff (kPa)	% Diff	(kPa/ CA°)	Diff (kPa/ CA°)	%Diff		Diff (HP)	% Diff
Neat Diesel #1	12331	-	-	844	-	-	84.7	-	-
5% MEOH	12787	+ 456	+ 3.7	783	- 61	- 7.2	85.4	- 0.7	- 0.8
10% MEOH	12858	+ 527	+ 4.3	907	+ 63	+ 7.5	82.4	- 2.3	- 2.7
15% MEOH	12813	+ 482	+ 3.9	1139	+295	+35.0	81.0	- 3.7	- 4.4
20% MEOH	12233	- 98	- 0.8	1347	+503	+59.6	76.4	- 8.3	- 9.8
25% MEOH	12220	-111	- 0.9	1441	+597	+70.7	74.1	-10.6	-12.5
15% MEOH + 0.1% DII	12637	+306	+ 2.5	965	+121	+14.3	79.7	- 5.0	- 5.9
25% MEOH + 0.2% DII	12359	+ 28	+ 0.2	1249	+405	+48.0	73.8	-10.9	-12.9
30% MEOH + 0.2% DII	12069	-262	- 2.1	1515	+671	+79.5	71.8	-12.9	-15.2
30% MEOH + 0.4% DII	12346	+ 15	+ 0.1	1530	+686	+81.3	71.5	-13.2	-15.6

TABLE 6: COMBUSTION ANALYSIS FOR TESTED FUELS VERSUS #1 BASELINE DIESEL FOR MAXIMUM LOAD

FUEL	Avg. Inj. Timing	Avg. C.A. for P_{max}	Diff. in C.A. for P_{max} vs Baseline		Avg. C.A. for ΔP_{max}	Diff. in C.A. for ΔP_{max} vs Baseline	
		C.A.	Diff C.A.	% Diff	C.A.	Diff C.A.	% Diff
Neat Diesel	337.8	363.6	-	-	349.1	-	-
5% MEOH	338.3	364.5	+ 0.9	+ 0.2	348.2	- 0.9	- 0.26
10% MEOH	336.8	363.4	- 0.2	- 0.05	347.4	- 1.7	- 0.49
15% MEOH	337.8	363.3	- 0.3	- 0.08	348.8	- 0.3	- 0.09
20% MEOH	338.0	363.5	- 0.1	- 0.03	350.0	+ 0.9	+ 0.26
25% MEOH	337.3	363.0	- 0.6	- 0.17	350.6	+ 1.5	+ 0.43
15% MEOH + 0.1% DII	336.9	363.5	- 0.1	- 0.03	347.8	- 1.3	- 0.37
25% MEOH + 0.2% DII	337.0	363.1	- 0.5	- 0.04	349.0	- 0.1	- 0.03
30% MEOH + 0.2% DII	337.8	362.5	- 1.1	0.30	350.8	+ 1.7	+ 0.49
30% MEOH + 0.4% DII	337.1	363.9	- 0.7	- 0.19	349.9	+ 0.8	+ 0.23

TABLE 7: TIMING OF COMBUSTION EVENTS VERSUS BASELINE FOR MAXIMUM LOAD

Fuel	$\overline{P\ max}$	$\overline{P\ max}$ vs. Baseline $\overline{P\ max}$		$\overline{\Delta P\ max}$	$\overline{\Delta P\ max}$ vs. Baseline $\overline{\Delta P\ max.}$		$\overline{HP}$	$\overline{HP}$ vs. Baseline $\overline{HP}$	
	(kPa)	Diff. (kPa)	% Diff.	(kPa/ C.A.)	Diff. (kPa/C.A.)	% Diff.		Diff. (HP)	% Diff.
#1 Diesel	12331	-	-	844	-	-	84.7	-	-
#1 Diesel + 2.5% DALCO	12980	+649	+5.2	908.8	+64.8	+7.6	86.2	+1.5	+1.7
#1 Diesel + 2.5% DALCO + 5% H_2O	12797	+466	+3.8	922.3	+78.3	+9.3	82.4	-2.3	-2.7
#1 Diesel + 2.75% DALCO + 5.5% H_2O	12837	+506	+4.1	767.0	-77.0	-9.1	87.2	+2.5	+2.9
#1 Diesel + 2.5% DALCO + 5.0% H_2O + DII	12908	+577	+4.6	951.1	+107.1	+12.7	82.1	-2.6	-3.1
#1 Diesel + 7.5% MEOH + 7.5% H_2O + 3.0% DALCO	12775	+444	+3.6	902	+ 58	+ 6.8	82.6	-2.1	-2.4

TABLE 8: COMBUSTION ANALYSIS FOR TESTED FUELS VERSUS #1 BASELINE DIESEL FOR MAXIMUM LOAD

Fuel	Avg. Inj. Timing	Avg. C.A. for P_{max}	Diff. in C.A. for P_{max} vs Baseline		Avg. C.A. for ΔP_{max}	Diff. in C.A. for ΔP_{max} vs Baseline	
	C.A.	C.A.	Diff C.A.	% Diff	C.A.	Diff C.A.	% Diff
# 1 Diesel	337.8	363.6	-	-	349.1	-	-
# 1 Diesel + 5% H_2O	338.1	364.4	+ 0.8	+ 0.22	347.9	- 1.2	- 0.34
# 1 Diesel + 15% MEOH + 0.15% H_2O + 0.15% DII	337.0	363.1	- 0.5	- 0.14	347.9	- 1.2	- 0.34
# 1 Diesel + 30% MEOH	337.3	364.0	+ 0.4	+ 0.11	351.5	+ 2.4	+ 0.68
1990 Diesel	335.9	362.9	- 0.7	- 0.19	346.9	- 2.2	- 0.63

TABLE 9: TIMING OF COMBUSTION EVENTS VERSUS BASELINE FOR MAXIMUM LOAD - #1 DIESEL

FUEL	P max	P max vs Baseline P max		ΔP max	ΔP max vs. Baseline ΔP max		$\overline{HP}$	$\overline{HP}$ vs. Baseline $\overline{HP}$	
	(kPa)	Diff (kPa)	% Diff	(kPa/ LA^{o})	Diff (kPa/ LA^{o})	% Diff	HP	Diff (HP)	% Diff
#1 Diesel (Baseline)	12331	-	-	844	-	-	84.7	-	-
# 1 Diesel + 5% H_2O	12907	+ 576	+ 4.7	744	- 100	- 11.8	84.4	- 0.3	-0.35
#1 Diesel + 15% MEOH + 2.5% H_2O + 0.15% DII	12748	+ 417	+ 3.4	1011	+ 167	+ 19.8	79.25	- 5.45	-6.43
#1 Diesel + 30% MEOH	12511	+ 180	+ 1.4	1771	+ 927	+ 109.8	72.3	- 12.4	-14.6
1990 Diesel	14290	+ 1959	+ 15.8	1175	+ 331	+ 39.2	94.8	+ 10.1	+11.92

TABLE 10: COMBUSTION ANALYSIS FOR TESTED FUELS VERSUS BASELINE FOR MAXIMUM LOAD - #1 DIESEL

Fuel	Avg. Inj. Timing	Avg. C.A. for P_{max}	Diff. in C.A. for P_{max} vs Baseline		Avg. C.A. for ΔP_{max}	Diff. in C.A. for ΔP_{max} vs Baseline	
	C.A. °	C.A. °	Diff C.A.°	% Diff	C.A. °	Diff C.A.°	% Diff
# 1 Diesel	337.8	363.6	-	-	349.1	-	-
# 1 Diesel + 2.5% DALCO	N/A	363.6	-	-	347.1	- 2.0	- 0.57
# 1 Diesel + 2.5% DALCO + 5% H_2O	336.1	363.4	- 0.2	- 0.05	347.5	- 1.6	- 0.45
# 1 Diesel + 2.75% DALCO+ 5.5% H_2O	N/A	364.1	+ 0.5	+ 0.13	347.6	- 1.5	- 0.43
# 1 Diesel + 2.5% DALCO + 5.0% H_2O + DII	N/A	363.5	- 0.1	- 0.03	347.5	- 1.6	- 0.45
#1 Diesel + 7.5% MEOH + 7.5% H_2O + 3.0% DALCO	N/A	363.5	- 0.1	- 0.03	347.4	- 1.7	- 0.48

TABLE 11: TIMING OF COMBUSTION EVENTS VERSUS BASELINE FOR MAXIMUM LOAD - #1 DIESEL

FUEL	P max	P max vs Baseline P max		ΔP max	ΔP max vs. Baseline ΔP max		$\overline{HP}$	$\overline{HP}$ vs. Baseline HP	
	(kPa)	Diff (kPa)	%Diff	(kPa/ CA°)	Diff (kPa/ CA°)	% Diff	HP	Diff (HP)	% Diff
# 2 Diesel	12632	-	-	769	-	-	85.9	-	-
#2 Diesel + 15% MEOH	12622	-10	-0.08	1235	+ 466	+ 60.6	77.3	-8.6	-10.0
#2 Diesel + 15% MEOH + DII	12756	+124	+0.98	978	+ 209	+ 27.2	80.5	-5.4	-6.3
#2 Diesel + 20% MEOH + DII	12624	- 8	-0.06	1155	+ 386	+ 50.2	77.66	-8.25	-9.6

TABLE 12: COMBUSTION ANALYSIS FOR TESTED FUELS VERSUS BASELINE DIESEL FOR MAXIMUM LOAD - #1 DIESEL

Fuel	Avg. Inj. Timing	Avg. C.A. for P_{max}	Diff. in C.A. for P_{max} vs Baseline		Avg. C.A. for ΔP_{max}	Diff. in C.A. for ΔP_{max} vs Baseline	
	C.A.	C.A.	Diff C.A.	% Diff	C.A.	Diff C.A.	% Diff
# 2 Diesel	236.8	365.5	-	-	349.1	-	-
# 2 Diesel + 15% MEOH	337.0	363.8	- 1.7	- 0.46	349.0	- 0.1	- 0.03
# 2 Diesel + 15% MEOH + DII	336.5	363.9	- 1.6	- 0.43	347.8	- 1.3	- 0.37
# 2 Diesel + 20% MEOH + DII	336.8	363.3	- 2.2	- 0.60	348.5	- 0.6	- 0.17

TABLE 13: TIMING OF COMBUSTION EVENTS VERSUS BASELINE FOR MAXIMUM LOAD - #2 DIESEL

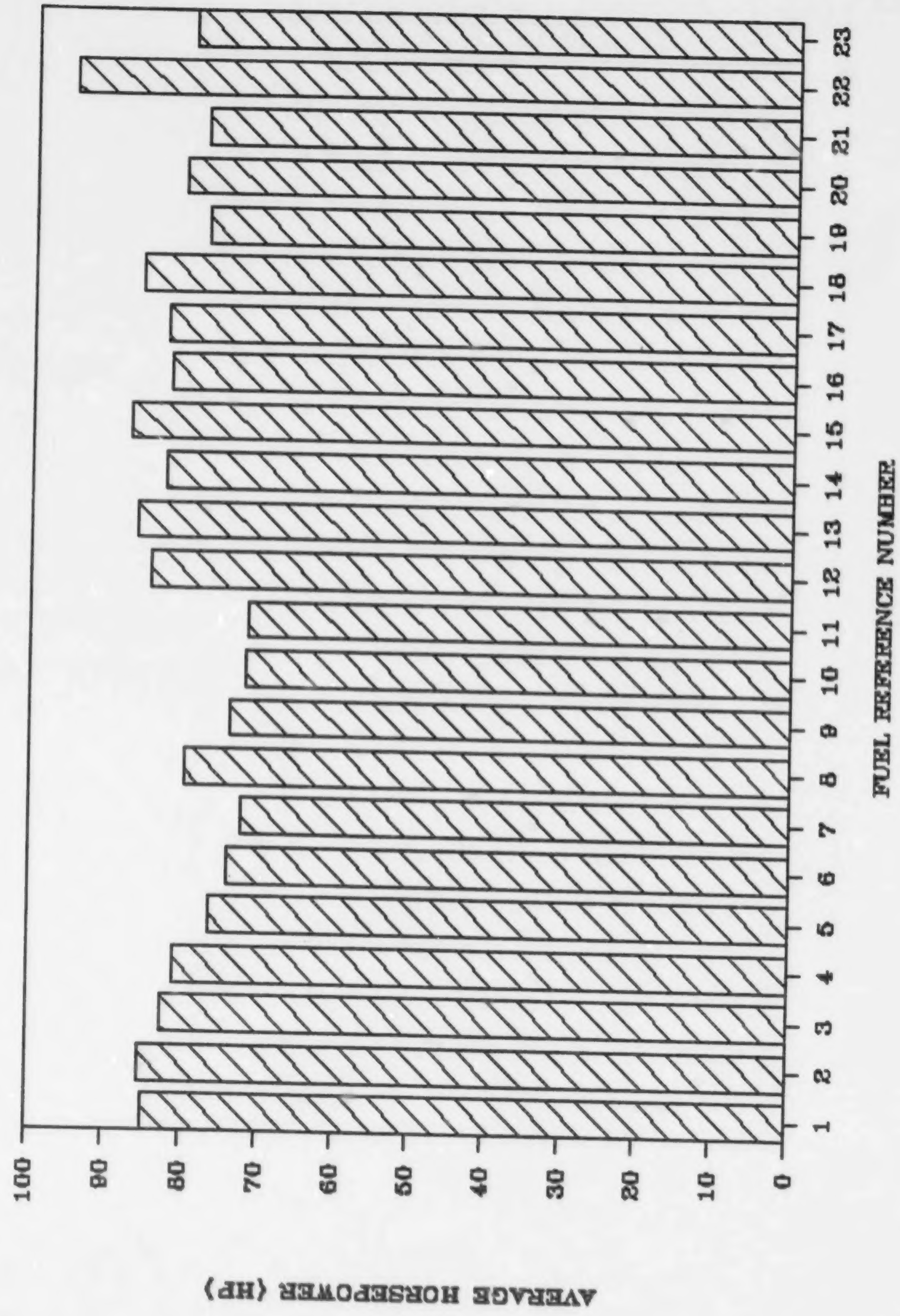

FIGURE 19: COMBUSTION ANALYSIS AT MAXIMUM LOAD
AVERAGE BRAKE HORSEPOWER

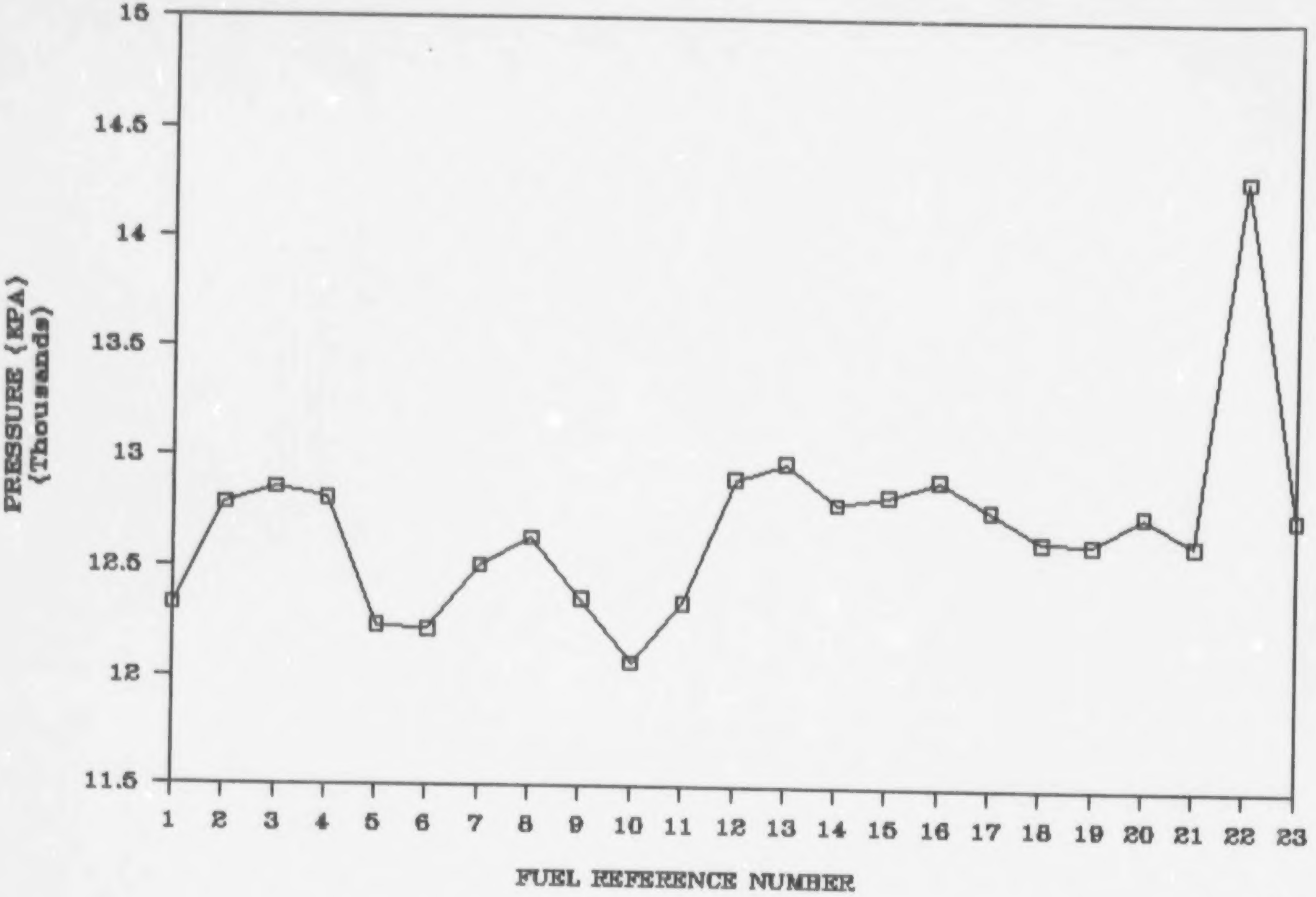

FIGURE 20: COMBUSTION ANALYSIS AT MAXIMUM LOAD

AVERAGE pmax

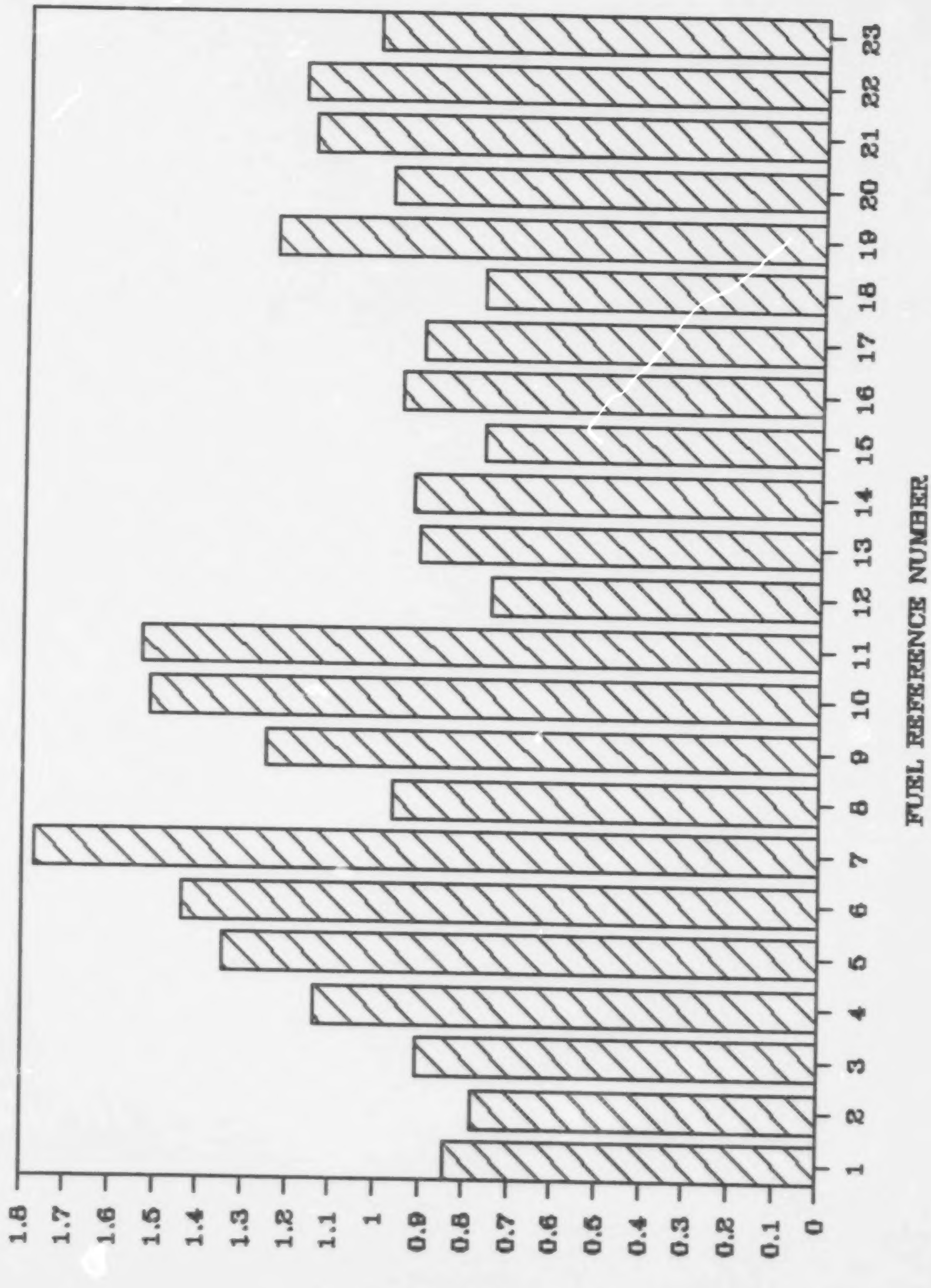

FIGURE 21: COMBUSTION ANALYSIS AT MAXIMUM LOAD
AVERAGE DELTA Pmax

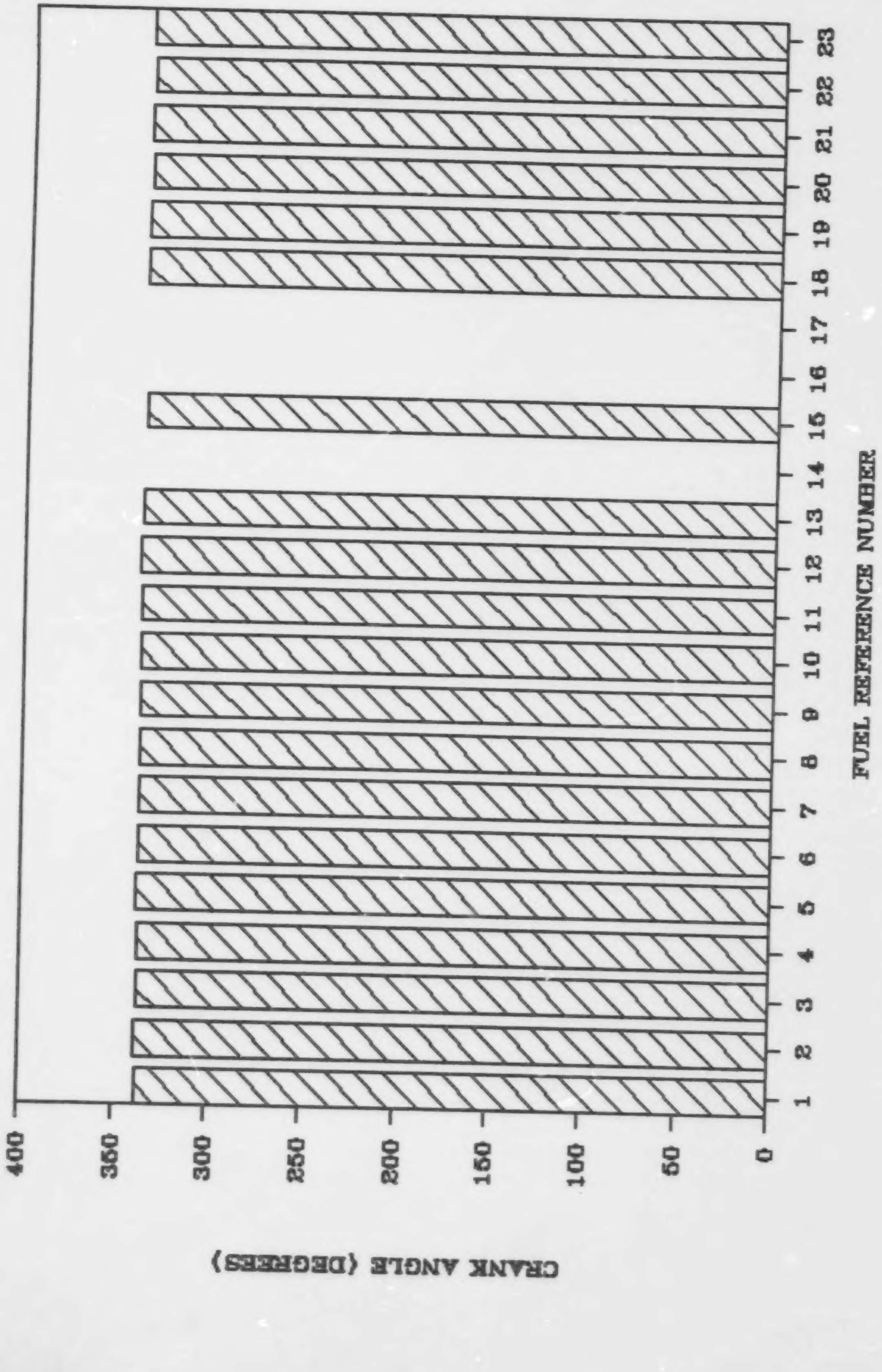

FIGURE 22: TIMING OF COMBUSTION EVENTS AT MAXIMUM LOAD
AVERAGE INJECTION TIMING

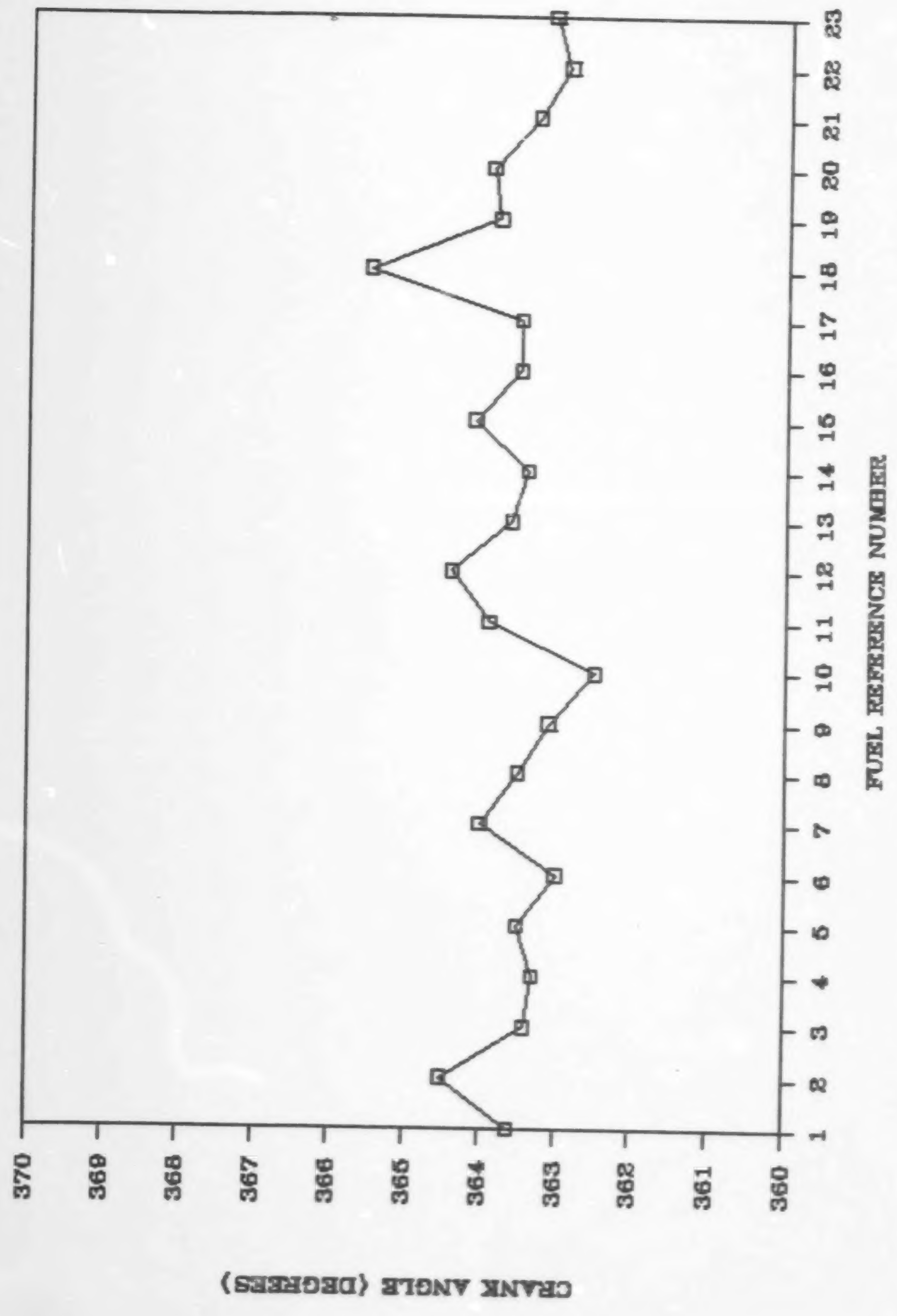

FIGURE 23: TIMING OF COMBUSTION EVENTS AT MAXIMUM LOAD
AVERAGE C.A. FOR Pmax

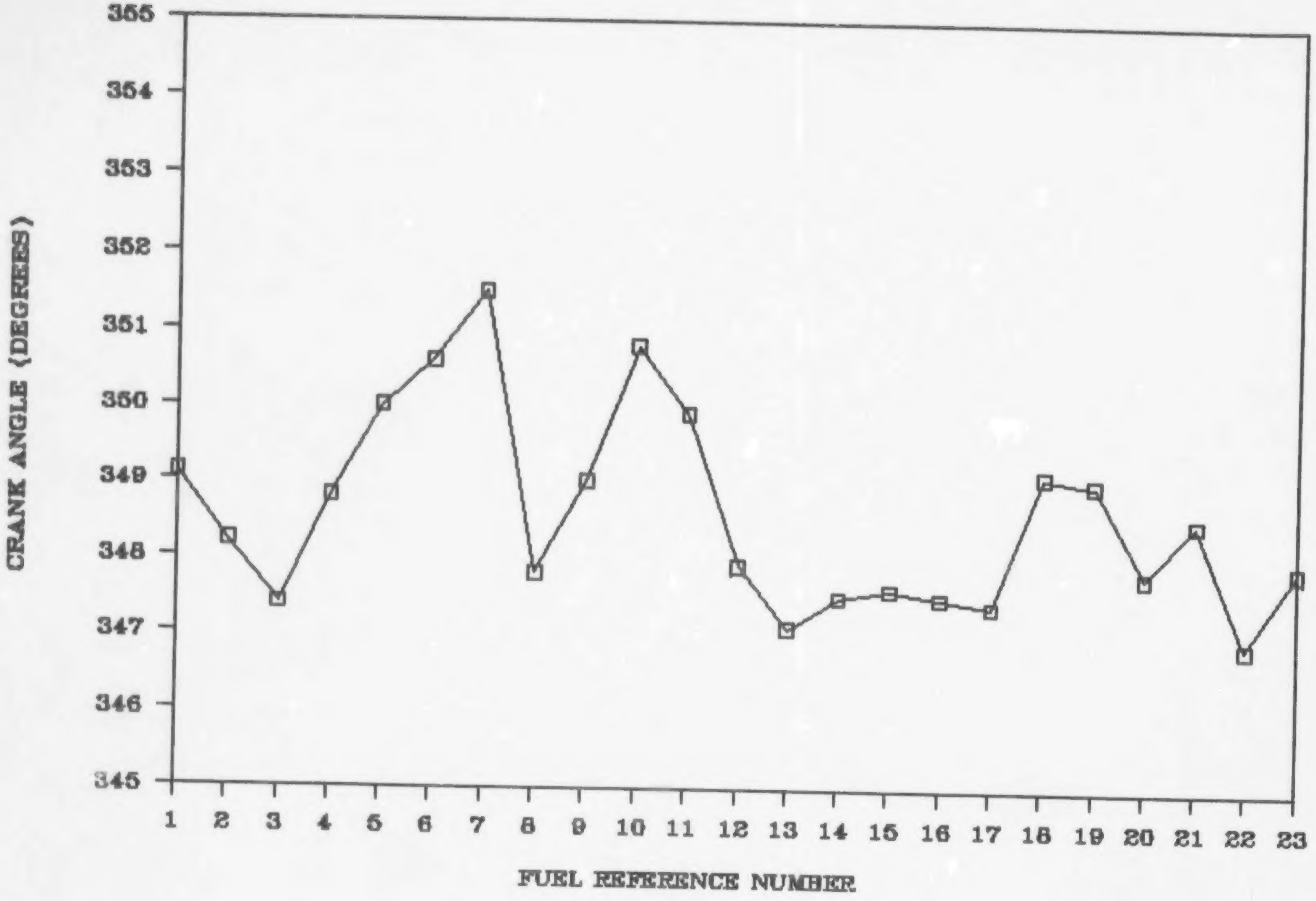

FIGURE 24: TIMING OF COMBUSTION EVENTS AT MAXIMUM LOAD
AVERAGE C.A. FOR DELTA Pmax

Gaseous emissions and particulate emission results for 5 selected load/speed settings for each fuel blend are presented in Tables 14 to 23 and graphed in Figures B1 to B50 located in Appendix B.

5.5.1 Performance (Torque Curve)

Performance results are graphically outlined in Figures A1-A92 in Appendix A. These figures map a torque curve for each fuel blend at rated load from 2600 to 1400 RPM. From these test results, average brake horsepower is calculated and tabulated in Tables 6-15. These results are plotted for each fuel in a comparative quantitative analysis in Figure 19. The average brake-horsepower results can be summarized by evaluating the fuel blends as follows:

- Diesel #1 + 0 - 30% MeOH (Ref. #1-7)
  - Average brake-horsepower at methanol levels above 5%, decreases almost linearly with constant increase in methanol content.
  - These results show how output brake-horsepower is directly affected by the decreased energy content in the fuel.
  - 5% methanol seems to enhance the combustion process resulting in slightly increased power.
- Diesel #1 + MeOH + DII (8-11)
  - Ignition improver has little or no effect on the output performance of this engine.

- Diesel #1 + H_2O (12)
  - Slight decrease in HP but not significant compared to Diesel #1 fuel.
- Diesel #1 DALCO (13)
  - Slight increase in HP but not significant compared to Diesel #1 fuel. It seems that DALCO has either a combustion enhancing effect or its energy density is similar to that of Diesel #2.
- Diesel #1 + DALCO + H_2O (14 + 15)
  - High DALCO and higher water content produced a slight increase in HP compared to Diesel #1 fuel.
- Diesel #1 + DALCO + H_2O + DII (16)
  - Comparable or decrease compared to similar blend without DII.
- Diesel #1 + DALCO + H_2O + MeOH (17)
  - Slight decrease compared to Diesel #1 fuel.
- Diesel #2 Fuel (18)
  - Slight increase compared to Diesel #1 fuel, due to higher energy density.

- Diesel #2 + MeOH Blends (20 + 21)
  - Increased methanol content causes a linear decrease in horsepower compared to Diesel #2 fuel.
- Diesel #2 + MeOH + DII
  - Slight increase in HP in comparison to blends without DII but still lower than Diesel #2 fuel.
- 1990 Fuel
  - Significant increase in HP in comparison to Diesel #1 fuel which is due to the significantly higher energy density of this fuel.

5.5.2 Combustion Analysis Results

The average maximum pressure and average ΔP maximum values over the torque curve are tabulated in Tables 6-13 and graphed in Figures 20 and 21.

The results for all the various fuel blends with respect to P max and ΔPmax are as follows:

- D#1 + MeOH Blends (0-30%) (1-7)
  - Pmax increases at low MeOH levels then decreases with MeOH content above 20% in comparison to D#1 fuel.

- ΔPmax increases significantly as MeOH content increases reaching a 110% increase with 30% methanol in comparison to D#1 fuel.

- This significant rise in ΔPmax is a critical factor in determining engine life and component wear.

o D#1 + MeOH + DII (8-11)

- Pmax decreases with the addition of ignition improver in comparison to D#1 + MeOH blends without ignition improver.

- ΔPmax decreases in comparison to D#1 + MeOH blends without ignition improver with the same methanol content.

o D#1 + H_2O (12)

- Pmax increases significantly compared to D#1 fuel.

- ΔPmax decreases slightly compared to D#1 fuel.

o D#1 + DALCO (13)

- Pmax increases compared to D#1 fuel.

- ΔPmax increases slightly compared to D#1 fuel.

o D#1 + DALCO + H_2O (14 + 15)

- Pmax increases compared to D#1 fuel.
- Δ Pmax is comparable to D#1 fuel.

o D#1 + DALCO + H_2O + DII (16)

- Pmax increases significantly compared to similar blends without ignition improver.
- ΔPmax increases compared to similar blends without ignition improver.

o D#1 + DALCO + H_2O + MeOH (17)

- Pmax increases significantly compared to D#1 fuel.
- ΔPmax increases compared to D#1 fuel.

o D#2 Fuel (18)

- Pmax increases in comparison to D#1 fuel.
- ΔPmax decreases in comparison to D#1 fuel.

o D#2 + 15% MeOH (19)

- Pmax is comparable to D#2 fuel.
- ΔPmax increases significantly compared to D#2 fuel.

- D#2 + MeOH + DII (20, 21)

  - Pmax increases compared to similar blends without ignition improver.
  - ΔPmax decreases compared to similar blends without ignition improver.

- 1990 Fuel (22)

  - Pmax is greatly increased compared to D#1 fuel (much higher than any other blend).
  - ΔPmax increases compared to D#1 fuel.

The average timing of combustion events are outlined in Figures 22 to 24. Average injection timing remained fairly constant due to the fuel injection pump being mechanically controlled.

General trends observed showed no major change in timing for Pmax but a significant ignition delay in ΔPmax as methanol content is increased in the blend.

5.5.3 Gaseous Emissions

i) Carbon Monoxide (g/BHPHr.)

All the CO_2 values are comparable for all the load speeds and blends utilized for the test program. The CO_2 values obtained for the idle conditions reflect the stability of the engine at that condition.

ii) Carbon Monoxide (g/BHPHr.)

- o D#1 MeOH Blends (0 to 30%) (Fuel REf. #1-7)
  - low loads show an increase in CO as %MeOH increases.
  - 75% load - slight increase but no significant increases.
  - full loads - decrease as % MeOH increased.
- o D#1 + MeOH + DII (8-11)
  - displays same characteristics as straight blends compared to D#1.
  - low loads show a decrease compared to the straight MeOH blends.
  - comparable to high load conditions of the straight MeOH blends.
- o D#1 + H_2O (12)
  - slight increases in CO but not significant compared to D#1 neat fuel.
- o D#1 + DALCO (13)
  - increase for all loads compared to D#1 fuel.

  - comparable at partial loads to D#1 + H_2O blends.

  - slight increase at full loads to D#1 + H_2O blends.

- D#1 + DALCO + H_2O (14 + 15)

  - comparable at lower loads to D#1 fuel.

  - increase at higher loads compared to D#1 fuel.

  - comparable to the D#1 + H_2O and D#1 + DALCO blends.

- D#1 + DALCO + H_2O + DII (16)

  - comparable at partial loads to D#1 + DALCO + H_2O without DII.

  - decrease at full loads compared to D#1 + DALCO + H_2O without DII.

- D#1 + DALCO + H_2O + MeOH (17)

  - comparable to D#1 fuel at 75% load speed.

  - decrease in comparison to D#1 fuel at full load conditions.

- o D#2 Fuel (18)
  - comparable to D#1 fuel.
- o D#2 Fuel + 15% MeOH (19)
  - general increase compared to D#2 fuel.
- o D#2 Fuel + 15% MeOH + DII (20)
  - general increased compared to D#2 + 15% MeOH blend.
- o D#2 Fuel + 20% MeOH + DII (21)
  - comparable or decrease compared to 15% MeOH + Blend + DII.
- o 1990 Fuel (22)
  - general increase compared to D#1 or D#2 fuel.

iii) THC Emissions (g/BHPHr.)

- general THC values are much greater at the lower loads for all blends in comparison to higher load settings.

- o D#1 + MeOH Blends (0-30%) (1-7)
  - low loads - THC increases as MeOH increases compared to D#1 fuel

- 75% loads - comparable (30% MeOH - OUTLIER MAJOR DECREASE) compared to D#1 fuel
- 100% loads - comparable as %MeOH increases.

o D#1 + 15, 25, 30% MeOH + DII (8 - 11)

- general decrease for partial loads compared to D#1 + MeOH blends without DII
- slight increase at 100% loads compared to D#1 + MeOH blends without DII
- comparison to D#1 Fuel is similar to D#1 + MeOH blends without DII.

o D#1 + 5% H_2O (12)

- increase at low loads compared to D#1 + low MeOH blends.
- comparable at remaining loads to D#1 + low MeOH blends.

o D#1 + 2.5% DALCO (13)

- decrease for all load conditions - compared to D#1.
- decrease for all load conditions - compared to D#1 + 5% H_2O.

- o D#1 + 2.5% DALCO + 5% H_2O (Also D#1 + 2.75% DALCO + 5.5% H_2O) (14 + 15)
  - slight increase for all loads compared to D#1 + 5% H_2O.
  - decrease for all loads compared to D#1.
  - decrease for all loads compared to D#1 + 5% H_2O.
- o D#1 + 2.5% DALCO + 5% H_2O + DII (16)
  - slight increase or comparable at partial loads compared to D#1 + 2.5% DALCO + 5% H_2O slight decrease.
- o D#1 + 3% DALCO + 7.5% + 7.5% MeOH (17)
  - at all loads - decrease compared to D#1.
  - at all loads - comparable to D#1 + 5% H_2O 2.5% DALCO.
- o D#2 (Diesel #2 Fuel) (18)
  - slight decrease or comparable at higher loads compared to D#1 fuel.

- D#2 + 15% MeOH (19)
  - general increase for low loads and 1600 rpm/100% load comparable to D#2 fuel.
- D#2 + 15% MeOH + DII (20)
  - increase at partial loads compared to D#2 + 15% MeOH blend.
  - comparable at full loads to D#2 + 15% MeOH blend.
- 1990 Fuel (22)
  - increase compared to D#2 and D#2 fuel for these (1800 rpm/75% load) speeds (2200 rpm/100% load) data inconclusive.

iv) Total N_{Ox} Emissions (g/BHPHr.)

- D#1 + MeOH Blends (0-30%) (1-7)
  - decreased at partial loads as %MeOH increased.
  - slight increase at 100% loads as % MeOH increased.
- D#1 + MeOH + DII (8-11)
  - increased at all loads compared to D#1 MeOH blends without DII.

- D#1 + 5% H_2O (12)
    - increase at idle compared to D#1 fuel.
    - remaining conditions are comparable to D#1 fuel.
- D#1 + 2.5% DALCO (13)
    - general decrease for all loads compared to D#1 + 5% H_2O.
    - general decrease for all loads compared to D#2 fuel.
- D#1 + 2.5% [illegible]CO + 5% H_2O (14)
    - slight increase for all loads compared to D#1 + 2.5% DALCO blend.
    - slight decrease or comparable to D#1 fuel.
- D#1 + 2.75% DALCO + 5.5% H_2O (15)
    - decrease at all loads compared to the 2.5% DALCO + 5% H_2O.
- D#1 + 2.5% DALCO + 5% H_2O + DII (16)
    - slight increase at idle compared to D#1 + 2.5% DALCO + 5% H_2O,

"

  - slight decrease at remaining loads compared to 2.5% DALCO + 5% H_2O.

- D#1 + 3% DALCO + 7.5% H_2O + 7.5% MeOH (17)

  - increase at higher loads compared to D#1 fuel.

- D#2 (18)

  - comparable to D#1.

- D#2 + 15% MeOH (19)

  - decrease at low loads compared to D#2 fuel.

  - increase at remaining loads compared to D#2 fuel.

- D#2 + 15% MeOH + DII (20)

  - increase at low loads compared to D#2 + 15% MeOH blend.

  - decrease or comparable at remaining loads compared to D#2 + 15% MeOH blend.

- D#2 + 20% MeOH + DII (21)

  - comparable to D#2 + 15% MeOH + DII.

- o 1990 Fuel (22)
    - slightly higher for all loads compared to D#2.

v) NO_2 (g/BHPHr.)

- o D#1 + MeOH Blends (0-30%) (1-7)
    - comparable all loads compared to D#1 fuel.
- o D#1 + MeOH + DII (8-11)
    - slight increase for all loads compared to D#1 + MeOH blends.
- o D#1 + H_2O (12)
    - slight increase for all loads compared to D#1.
- o D#2 (18)
    - comparable at all loads to D#2 fuel.
- o D#2 + 15% MeOH (19)
    - at low loads comparable to D#2 fuel.
    - increase at higher loads compared to D#2 fuel.

- o D#2 + 15% MeOH + DII (20)
  - inconclusive.
- o D#2 + 20% MeOH + DII (21)
  - inconclusive.
- o 1990 Fuel (22)
  - increase overall compared to D#2 and D#2 fuels.

vi) NO (g/GHPHr.)

- o D#1 + MeOH Blends (0-30%) (1-7)
  - increase at low loads (and 100% loads - as %MeOH increased NO increased.
  - slight decrease at the 75% load with the higher % MeOH blends.
- o D#1 + MeOH + DII (8-11)
  - increased over all load speeds compared to D#1 + MeOH blends without DII.
- o $D\#1 + H_2O$ (12)
  - increase at idle condition compared to D#1 fuel.

  - slight decrease at remaining loads compared to D#1 fuel.

- D#1 + DALCO (13)
  - decrease at all loads compared to D#1 + H_2O.
  - slight decrease or comparable at all loads compared to D#1 fuel.

- D#1 + 2.5% DALCO + 5% H_2O (14)
  - slight increase for all loads compared to D#1 + 2.5% DALCO.
  - comparable at all loads to D#1 + 5% H_2O.
  - slight decrease at all loads compared to D#1.

- D#1 + 2.75% DALCO + 5.5% H_2O (15)
  - slight decrease at all loads compared to the 2.5% DALCO + 5% H_2O.

- D#1 + 3% DALCO + 7.5% H_2O + 7.5% MeOH (17)
  - increase at all loads compared to D#1 + DALCO + HO blends.
  - comparable at all loads compared to D#1 fuel.

- D#2 (18)
    - comparable at all loads to D#1 fuel.
- D#2 + 15% meOH (19)
    - decrease at low loads compared to D#2 fuel.
    - increase at remaining loads compared to D#2 fuel.
- D#2 + 15% MeOH + DII (20)
    - increase for all load speeds compared to D#2 + 15% MeOH blend.
- D#2 + 20% MeOH (21)
    - slightly lower or comparable at all loads to D#2 + 15% MeOH + DII.
- 1990 Fuel (22)
    - comparable at all loads to D#1 fuel.
    - comparable or slightly higher at all loads to D#2 fuel.

5.5.4 Particulate Analysis (g/BHPHr.)

i) Total Particulates (g/BHPHr.)

- o D#1 + MeOH Blends (0-30%)
  - idle - as %MeOH increased total particulates increased.
  - 2200 rpm/100% load as - %MeOH increased total particulates increased.
  - comparable or slight decrease at remaining loads compared to D#1 fuel assuming D#1 at 1600 rpm/100% load artificially high.
- o D#1 + 15, 25, 30% MeOH + DII (8-11)
  - comparable at 1600 rpm/100% load in comparison to D#1 + MeOH blends without DII.
  - increased at remaining loads in comparison to D#1 + MeOH blends without DII.
  - increase of particulates with 30% MeOH when the DII level increased.

- o D#1 + 5% H_2O (12)
  - increase at idle compared to D#1 fuel.
  - lower or comparable at remaining loads compared to D#1 fuel.
- o d#1 + 2.5% DALCO (13)
  - lower or comparable at all loads compared to D#1 fuel.
  - (exception is 1600/100% load, increases compared to D#1).
- o D#1 + 2.5% DALCO + 5% H_2O (14)
  - increase at all loads compared to D#1 fuel.
  - (exception 1600 rpm/100% load) where an increase observed.
- o D#1 + 2.75% DALCO + 5.5% H_2O (15)
  - increase observed when no data 1400 rpm/25% load and idle.
- o D#1 + 2.5% DALCO + 5% H_2O + 0.15% DII (16)
  - increase at all loads compared to D#1.
  - increase at all loads compared to D#1 + DALCO + H_2O blends.

- D#1 + 3% DALCO + 7.5% H_2O + 7.5% MeOH (18)
  - no data 1400/25% load and idle.
  - slightly lower or comparable for remaining loads compared to D#1 + DALCO + H_2O blends with and without DII.
  - slightly lower or comparable for remaining loads compared to D#1 and D#2 fuels.
- D#2 (18)
  - comparable at all loads (except 1600 rpm/100%) to D#1.
- D#2 + 15% MeOH (19)
  - slightly higher for all costs compared to D#2 fuel.
- D#2 + 15% MeOH + DII (20)
  - comparable or slightly lower at all loads compared to D#2 + 15% MeOH.
- D#2 + 20% MeOH + DII (21)
  - comparable to D#2 + 15% MeOH + DII.

- o 1990 Fuel (22)
  - increase at low loads compared to D#1 and D#2 fuels.
  - comparable or slightly higher at remaining loads compared to D#1 and D#2 fuels.

ii) % Soluble Particulates

- o D#1 + MeOH Blends (0-30%) (1-7)
  - general increase as % MeOH increased for all load speeds compared to D#1 fuel.
- o D#1 + 15%, 25, 30% MeOH + DII (8-11)
  - partial loads - comparable to D#1 + MeOH blends.
  - full loads - 25% and 30% blends show slight increase compared to D#1 + meOH blends.
  - 15% MeOH + DII comparable to D#1 + 15% MeOH blend.
- o D#1 + 5% H_2O (12)
  - slight increase at all loads compared to D#1 fuel.

- D#1 + 2.5% DALCO (13)
  - slight increase at all loads compared to D#1 fuel.
  - slightly over or comparable at all loads compared to D#1 + 5% H_2O blend.
- D#1 + 2.5% DALCO + 5% H_2O (14 + 15)
  - increase at all loads compared to D#1 fuel.
  - increase at all loads compared to D#1 + 2.5% DALCO.
  - increase at all loads compared to D#1 + 5% H_2O.
- D#1 + 2.75% DALCO + 5% H_2O + 15% DII (16)
  - comparable to previous D#1 + H_2O and/or DALCO blends at all loads compared to D#1 fuel.
- D#2 (18)
  - comparable at all loads to D#1 fuel.
- D#2 + 15% MeOH (19)
  - increase at all loads compared to D#2 fuel.

- o D#2 + 15% MeOH + DII (20)
  - increase at all loads compared to D#2 fuel.
  - increase at all loads compared to D#2 + MeOH blend.
- o D#2 + 20% MeOH + DII (21)
  - idle - comparable to D#2 + 15% MeOH + DII.
  - 100% loads - increase compared to D#2 + 15% MeOH + DII 75% load - inconclusive.
- o 1990 Fuel (22)
  - higher or comparable at all loads compared to D#1 and D#2 fuels.

iii) Soluble Particulates (g/BHPHr.)

- o D#1 + MeOH Blends (0-30%) (1-7)
  - as % MeOH increased; soluble increased at all loads compared to D#1 fuel.
- o D#1 + 15, 25, 30% MeOH + DII (8-11)
  - general increase at all loads compared to D#1 + MeOH blends.

- D#1 + 5% H_2O (12)
  - slight increase or comparable at all loads compared to D#1 fuel.
- D#1 + 2.5% DALCO (13)
  - slightly lower or comparable at all load/speeds.
- D#1 + 2.5% DALCO + 5% H_2O (14)
  - compared to D#1 - increases at low load conditions.
  - comparable at remaining load/speeds.
  - compared to DALCO + H_2O Emulsion - general increase over all load/speeds.
- D#1 + DALCO + H_2O + DII (15)
  - increase at low load settings compared to D#1 fuel.
  - comparable at higher load settings compared to D#1 fuel.
  - decrease at all load settings compared to D#1 + DALCO + H_2O blend.

- 1990 Fuel (22)
  - increase at low loads compared to D#1 and D#2 fuels.
  - comparable at higher loads compared to D#1 and D#2 fuels.

iv) Insoluble Particulates (g/BHPHr.)

- D#1 + MeOH Blends (0-30%) (1-7)
  - idle condition - increase as %MeOH increased.
  - decrease for all remaining load/speeds as %MeOH increased.
- D#1 + 15, 25, 30 MeOH + DII (8-11)
  - inconclusive for idle conditions.
  - remaining load conditions are comparable or show an increase in comparison to D#1 + MeOH blends.
- D#1 + 5% H_2O (12)
  - idle shows an increase compared to D#1 fuel.
  - remaining load speeds comparable or lower than D#2 fuel.

- o D#1 + 2.5% DALCO (13)
  - 100% loads - comparable to D#1 fuel.
  - partial load speeds show a decrease compared to D#1 fuel.
- o D#1 + DALCO + H_2O (14 + 15)
  - comparable at 1400 rpm/25% load and idle in comparison to D#1 fuel.
  - remaining loads comparable or slight decrease to D#1 fuel.
  - decrease at all loads when the blend of D#1 + 2.5% DALCO + 5.5% H_2O was increased to D#1 + 2.75% DALCO + 5.5% H_2O.
- o D#1 + DALCO + H_2O + DII (16)
  - general increase to D#1 fuel (exception 1600 rpm 100% load)
  - increased at partial load settings and 2200/100% load compared to D#1 + DALCO + H_2O without DII.
  - comparable at 1600 rpm/100% load in comparison to D#1 + DALCO + H_2O without DII.

- D#2 Fuel (18)
  - comparable at all loads to D#1.
- D#2 + 15% MeOH (19)
  - slight increase at idle compared to D#2 fuel.
  - decrease at remaining loads compared to D#2 fuel.
- D#2 + 15% MeOH + DII (20)
  - general decrease for all load speeds compared to D#2 fuel.
  - general decrease for all load speeds compared to D#2 + 15% MeOH blend.
- D#2 + 20% MeOH + DII (21)
  - decrease at partial loads in comparison to D#2 + 15% MeOH + DII.
  - comparable at 100% loads compared to D#2 + 15% MeOH + DII.
- 1990 Fuel (22)
  - shows a slight increase or comparable at partial loads to D#1 and D#2 fuels.
  - 100% loads - inconclusive.

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	3360.6	3871.4	3322	3528.2	3143.6	3823	3309.3	4104.8	3579.8	3157.4
1400	50	N/A	723.5	746.3	742.8	734.5	732.7	730	779.6	739.8	732.2	745
1800	150	514.9	534.4	536.9	552.3	554.9	561.3	476.1	551	546.7	548.4	550.8
1600	245	540.4	508.6	518.4	518.3	526.5	525	541.2	525.3	524.7	522.4	516.6
2200	220	501.9	505.8	518.7	529.9	538.3	533.4	567.6	541.9	533.3	526.3	533.6

SPEED RPM	LOAD LB-FT	5% H2O	2.5% DALCO	5% H2O 2.5% DALCO	5.5% H2O 2.75% DALCO	DII 5% H2O 2.5% DALCO	DII 7.5% H2O 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	5020.1	2816.1	3630.4	N/A	3334.8	3759.1	2939	2592.6	3782.7	3423.4	4226.8
1400	50	748.1	669.9	733	N/A	686.4	809.3	751.3	724.7	721.4	731.5	770.5
1800	150	542.6	501.1	539.7	506.2	481.7	564.4	523.9	636.3	544.3	552.7	549.3
1600	245	521.7	481.5	510.3	474.6	407.6	490.6	493.5	522.8	492.5	513.8	532.1
2200	220	533.4	427.3	519.5	490.2	478	587.6	500.6	531.4	515.3	519.6	527.6

TABLE 14: CARBON DIOXIDE (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	27.13	36.83	30.62	39.31	38.5	69.72	26.77	36.7	39.05	33.47
1400	50	N/A	3.05	3.21	3.57	3.9	4.06	4.95	3.33	3.3	3.85	3.64
1800	150	1.37	1.32	1.34	1.42	1.42	1.42	0.48	1.17	1.01	1.08	0.93
1600	245	1.27	1.12	1.07	1.03	1.06	1.14	0.61	0.98	0.95	0.85	0.97
2200	220	1.33	1.58	1.49	1.35	1.42	1.3	1.6	1.82	1.69	1.32	1.65

SPEED RPM	LOAD LB-FT	5% H2O	2.5% DALCO	5% H2O 2.5% DALCO	5.5% H2O 2.75% DALCO	DII 5% H2O 2.5% DALCO	DII 7.5% H2O 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	49.39	14.23	24.69	N/A	26.84	N/A	23.41	34.51	37.86	35.91	81.07
1400	50	3.36	1.72	2.08	N/A	2.27	N/A	2.08	3	3.85	4.35	3.56
1800	150	1.42	0.7	0.72	0.87	0.73	0.83	0.99	0.26	1.33	1.33	0.25
1600	245	0.9	0.41	0.45	0.46	0.37	0.41	0.71	0.89	0.76	0.71	2.55
2200	220	1.46	0.63	0.8	0.71	0.59	0.84	1.33	0.35	1.47	1.48	0.85

TABLE 15: TOTAL HYDROCARBONS AS METHANE (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	24.03	71.12	75.86	100.23	114.92	218.25	61.92	93.9	112.26	92.06
1400	50	N/A	1.88	3.86	5.09	7.55	9.92	15.89	4.16	5.87	9.4	8.5
1800	150	0.13	0.19	0.3	0.32	0.19	0.41	0.4	0.35	0.44	0.5	0.45
1600	245	2.14	2.21	1.33	1.65	1.05	1.26	1.43	1.78	1.4	0.77	1.16
2200	220	0.7	0.68	0.7	0.66	0.51	0.62	0.67	0.75	0.63	0.66	0.66

SPEED RPM	LOAD LB-FT	5% H20	2.5% DALCO	5% H20 2.5% DALCO	5.5% H20 2.75% DALCO	DII 5% H20 2.5% DALCO	DII 7.5% H20 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	48.4	35.09	61.22	N/A	47.42	N/A	31.45	54.24	67.17	48.63	75.84
1400	50	2.67	3.35	2.98	N/A	3.84	N/A	2.69	6.64	3.86	4.63	4.68
1800	150	0.19	0.4	0.33	0.21	0.2	0.21	0.24	2.56	0.29	0.31	1.34
1600	245	2.54	3.36	3.21	1.55	1.38	0.95	2.24	1.14	1.58	1.22	1.01
2200	220	0.57	0.81	1	0.66	0.36	0.34	1.19	2.22	0.49	0.51	1.35

TABLE 16: CARBON MONOXIDE (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	50.94	51.47	37.54	30.8	21.92	13.86	40.73	39.92	25.8	23.66
1400	50	N/A	14.08	13.55	12.36	10.47	8.72	6.12	14.44	10.95	8.26	9.53
1800	150	13.23	13.68	13.75	13.92	13.66	12.9	10.62	13.74	13.41	13.18	13.38
1600	245	11.04	10.79	11.3	11.23	11.68	11.47	11.62	11.24	11.35	11.65	11.57
2200	220	11.01	11.41	12.15	11.81	12.46	12.66	12.68	12.4	12.29	12.43	12.08

SPEED RPM	LOAD LB-FT	5% H2O	2.5% DALCO	5% H2O 2.5% DALCO	5.5% H2O 2.75% DALCO	DII 5% H2O 2.5% DALCO	DII 7.5% H2O 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	76.56	45.24	50.35	N/A	55.11	N/A	45.79	28.2	49.59	37.36	45.67
1400	50	13.61	12.91	13.01	N/A	12.11	N/A	14.98	11.33	12.14	11.18	12.7
1800	150	13.18	11.87	12.95	11.3	10.85	13.06	12.53	14.78	12.97	12.81	14.2
1600	245	10.31	9.49	10.15	9.47	8.07	10.33	10.01	10.85	10.97	10.74	10.73
2200	220	11.11	8.46	10.66	10.27	9.65	12.17	10.63	11.45	12.02	11.47	11.29

TABLE 17: NITRIC OXIDE (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	27.88	31.14	30.18	31.58	20.22	26.22	29.25	33.61	31.59	27.63
1400	50	N/A	6.14	6.2	6.32	4.94	5.21	4.93	7.03	5.72	5.69	5.61
1800	150	6.52	6.84	6.75	6.98	5.96	6.04	6.74	7.56	6.9	7.64	6.76
1600	245	4.4	4.37	3.53	4.21	4.84	3.21	5.94	5.54	5.55	7.02	6.23
2200	220	5.44	5.46	5.21	5.86	5.67	8.21	6.51	5.87	6.23	6.82	7.41

SPEED RPM	LOAD LB-FT	5% H20	2.5% DALCO	5% H20 2.5% DALCO	5.5% H20 2.75% DALCO	DII 5% H20 2.5% DALCO	DII 7.5% H20 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	41.97	27.84	31.09	N/A	30.86	N/A	26.03	23.96	36.96	29.44	34.74
1400	50	6.59	7.03	6.06	N/A	6.72	N/A	7.34	5.4	6.78	8.79	7.43
1800	150	7.7	7.6	8.85	7.41	8.05	9.13	7.43	9.12	8.12	7.75	4.67
1600	245	4.89	4.07	4.55	4.58	4.08	5.81	4.7	6.23	4.72	5.88	4.88
2200	220	5.84	4.54	6.97	5.31	6.18	8.27	5.45	6.86	7.72	5.86	7.26

TABLE 18: NITROGEN DIOXIE (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	N/A	105.99	110.06	87.74	78.81	53.82	47.48	91.71	94.82	71.16	63.9
1400	50	N/A	27.72	26.98	25.26	20.98	18.59	14.31	29.17	22.51	18.35	20.22
1800	150	26.8	27.81	27.84	28.32	26.91	25.82	23.36	28.63	27.46	27.85	27.28
1600	245	21.33	20.92	20.85	21.42	22.75	20.79	23.75	22.79	22.97	24.88	23.98
2200	220	22.32	22.95	23.84	23.96	24.78	27.62	25.95	24.88	25.08	25.88	25.93

SPEED RPM	LOAD LB-FT	5% H2O	2.5% DALCO	5% H2O 2.5% DALCO	5.5% H2O 2.75% DALCO	DII 5% H2O 2.5% DALCO	DII 7.5% H2O 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	159.36	97.21	108.3	N/A	115.36	N/A	96.24	67.2	112.99	86.74	104.77
1400	50	27.45	26.83	26.01	N/A	25.29	N/A	30.31	22.77	25.4	25.93	26.9
1800	150	27.91	25.81	28.71	24.74	24.68	29.15	26.64	31.78	28	27.39	26.45
1600	245	20.7	18.61	20.13	19.11	16.45	21.65	20.05	22.86	21.55	22.36	21.33
2200	220	22.87	17.5	23.32	21.06	20.98	26.93	21.75	24.43	26.15	23.45	24.57

TABLE 19: TOTAL OXIDES OF NITROGEN (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	0.556	1.221	1.601	0.868	1.443	1.387	2.290	1.451	1.734	1.793	2.116
1400	50	0.121	0.147	0.145	0.113	0.123	0.117	0.200	0.210	0.177	0.216	0.210
1800	150	0.083	0.092	0.091	0.075	0.073	0.091	0.075	0.090	0.107	0.117	0.109
1600	245	0.109	0.072	0.073	0.062	0.054	0.061	0.056	0.073	0.059	0.060	0.060
2200	220	0.085	0.083	0.083	0.106	0.091	0.112	0.118	0.125	0.142	0.146	0.147

SPEED RPM	LOAD LB-FT	5% H20	2.5% DALCO	5% H20 2.5% DALCO	5.5% H20 2.75% DALCO	DII 5% H20 2.5% DALCO	DII 7.5% H20 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	1.340	0.665	1.665	0.000	1.648	0.000	0.647	0.670	0.818	0.678	3.125
1400	50	0.094	0.092	0.195	0.000	0.207	0.000	0.097	0.105	0.101	0.069	0.217
1800	150	0.046	0.053	0.070	0.059	0.097	0.059	0.057	0.093	0.067	0.068	0.080
1600	245	0.089	0.110	0.123	0.093	0.088	0.050	0.000	0.063	0.057	0.070	0.070
2200	220	0.091	0.086	0.099	0.088	0.107	0.109	0.085	0.101	0.082	0.101	0.110

TABLE 20: TOTAL PARTICULATES (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	0.312	0.964	1.340	0.652	1.123	1.118	1.954	1.009	1.461	1.527	1.818
1400	50	0.068	0.112	0.107	0.096	0.085	0.088	0.167	0.166	0.155	0.171	0.174
1800	150	0.037	0.062	0.070	0.056	0.049	0.072	0.053	0.060	0.083	0.088	0.083
1600	245	0.013	0.012	0.025	0.027	0.022	0.033	0.026	0.028	0.031	0.036	0.039
2200	220	0.033	0.052	0.063	0.082	0.066	0.081	0.085	0.102	0.114	0.117	0.121

SPEED RPM	LOAD LB-FT	5% H20	2.5% DALCO	5% H20 2.5% DALCO	5.5% H20 2.75% DALCO	DII 5% H20 2.5% DALCO	DII 7.5% H20 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	0.826	0.531	1.403	0.000	1.148	0.000	0.419	0.398	0.588	0.478	2.744
1400	50	0.065	0.058	0.145	0.000	0.110	0.000	0.052	0.074	0.064	0.049	0.165
1800	150	0.022	0.027	0.036	0.036	0.025	0.039	0.021	0.063	0.051	0.039	0.039
1600	245	0.016	0.018	0.037	0.013	0.013	0.020	0.018	0.020	0.019	0.025	0.017
2200	220	0.046	0.038	0.048	0.049	0.026	0.079	0.033	0.067	0.056	0.075	0.033

TABLE 21: SOLUBLE PARTICULATES (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	0.244	0.258	0.263	0.216	0.320	0.270	0.336	0.443	0.275	0.268	0.298
1400	50	0.053	0.035	0.038	0.018	0.038	0.029	0.033	0.043	0.022	0.045	0.036
1800	150	0.046	0.030	0.029	0.019	0.024	0.019	0.022	0.030	0.024	0.029	0.025
1600	245	0.096	0.059	0.052	0.036	0.031	0.028	0.030	0.044	0.028	0.024	0.022
2200	220	0.052	0.030	0.029	0.024	0.025	0.031	0.032	0.023	0.028	0.029	0.026

SPEED RPM	LOAD LB-FT	5% H2O	2.5% DALCO	5% H2O 2.5% DALCO	5.5% H2O 2.75% DALCO	DII 5% H2O 2.5% DALCO	DII 7.5% H2O 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	0.514	0.134	0.261	0.000	0.500	0.000	0.227	0.272	0.230	0.200	0.379
1400	50	0.028	0.034	0.051	0.000	0.097	0.000	0.044	0.031	0.037	0.020	0.052
1800	150	0.024	0.026	0.034	0.023	0.072	0.020	0.036	0.030	0.016	0.030	0.041
1600	245	0.073	0.092	0.086	0.080	0.075	0.031	0.091	0.044	0.038	0.046	0.053
2200	220	0.045	0.049	0.051	0.039	0.081	0.030	0.052	0.034	0.026	0.026	0.077

TABLE 22: INSOLUBLE PARTICULATES (g/BHPHr.)

SPEED RPM	LOAD LB-FT	NEAT DIESEL	5% MEOH	10% MEOH	15% MEOH	20% MEOH	25% MEOH	30% MEOH	DII 0.1 15% MEOH	DII 0.2 25% MEOH	DII 0.2 30% MEOH	DII 0.4 30% MEOH
910	6	56.32	78.83	83.13	75.27	77.73	80.51	85.3	69.46	84.27	85.44	85.82
1400	50	56.03	75.72	73.4	84.73	69.06	75.31	83.67	77.5	87.84	79.29	82.74
1800	150	45.23	67.52	70.44	74.73	66.88	78.67	70.98	67.11	77.53	75.35	76.7
1600	245	12.06	17.22	32.95	42.45	41.71	53.8	46.84	38.89	52.62	59.39	63.96
2200	220	39.3	63.19	68.77	77.09	72.77	72.62	72.62	81.92	80.24	79.85	82.36

SPEED RPM	LOAD LB-FT	5% H20	2.5% DALCO	5% H20 2.5% DALCO	5.5% H20 2.75% DALCO	DII 5% H20 2.5% DALCO	DII 7.5% H20 3% DALCO	D#2	D#2 15% MEOH	D#2 15% MEOH DII	D#2 20% MEOH DII	1990
910	6	61.79	79.74	84.27		69.66		64.79	59.81	71.47	70.28	87.84
1400	50	69.57	63.4	74.27		52.95		54.13	70.13	64.35	70.95	76.14
1800	150	48.48	50.44	51.87	61.76	26.07	65.67	37.14	68.4	75.75	56.66	48.32
1600	245	18.24	16.19	29.9	13.77	14.59	39.16	14.18	30.98	33.33	35	23.95
2200	220	50.3	43.83	48.63	55.64	24.66	71.68	38.18	66.16	68.5	74.6	30.56

TABLE 23: SOLUBLE ORGANICS (PERCENT)

FIGURE 25: COMPARISON OF PRESSURE TRACES AT 1600 RPM AT RATED LOAD

TOP CURVE: #1 DIESEL + 30% MeOH
BOTTOM CURVE: #1 NEAT DIESEL

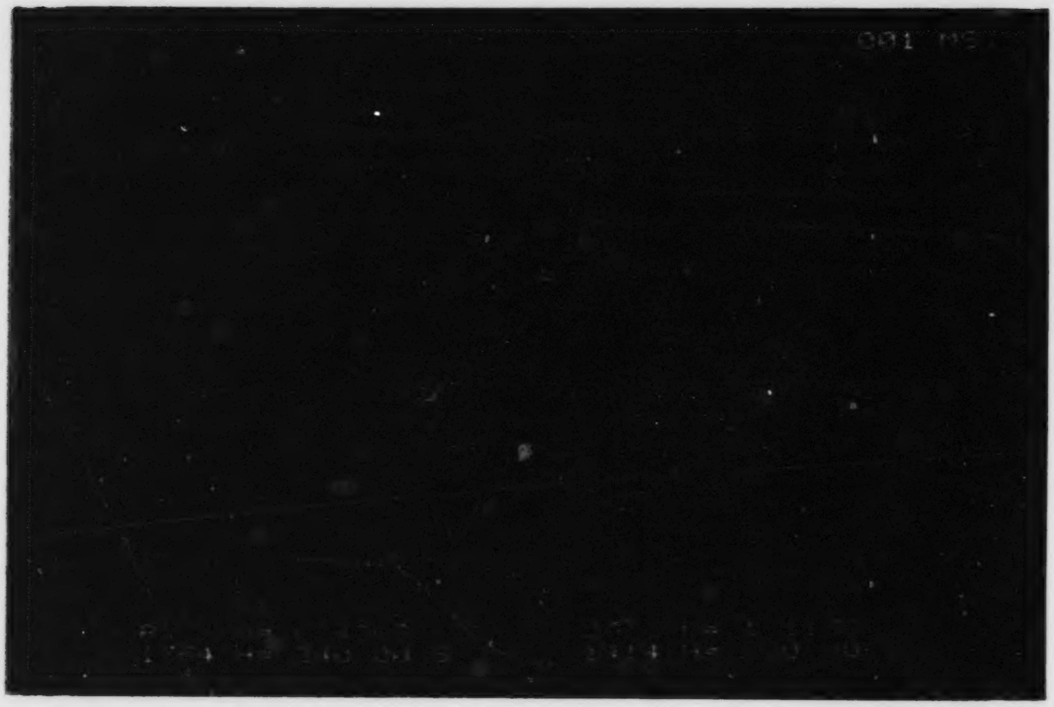

FIGURE 26: COMPARISON OF PRESSURE TRACES AT 1600 RPM AT RATED LOAD

TOP CURVE: #1 DIESEL + 30% MeOH
BOTTOM CURVE: #1 DIESEL + 10% MeOH

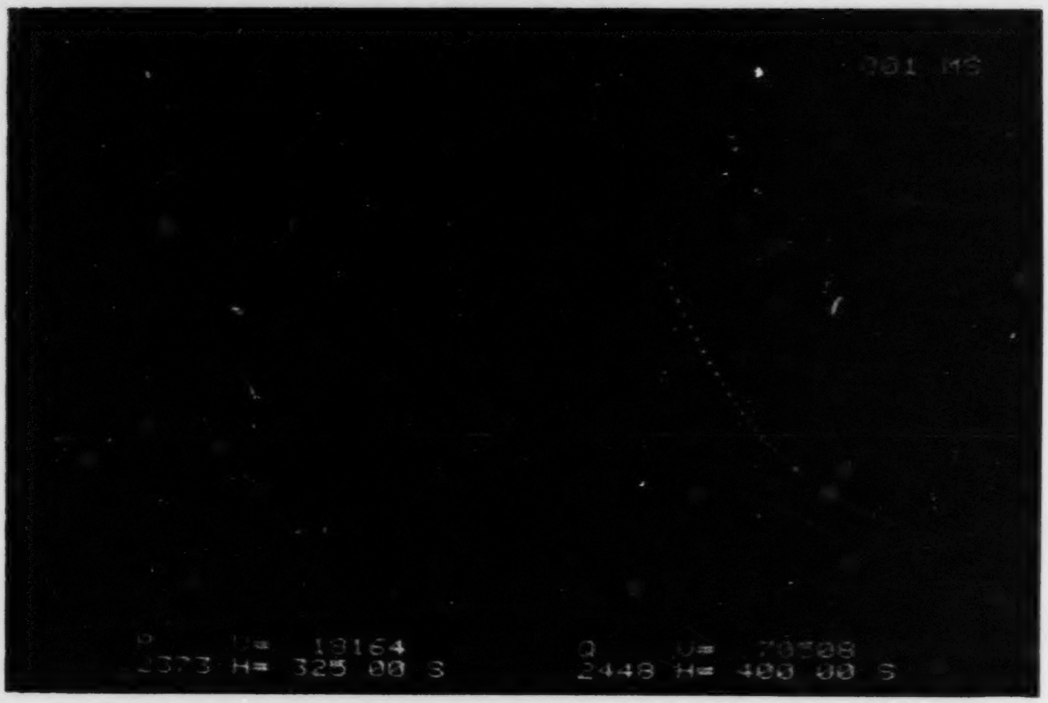

FIGURE 27: COMPARISON OF PRESSURE TRACES AT 1600 RPM AT RATED LOAD

TOP CURVE: 1990 DIESEL
BOTTOM CURVE: #1 NEAT DIESEL

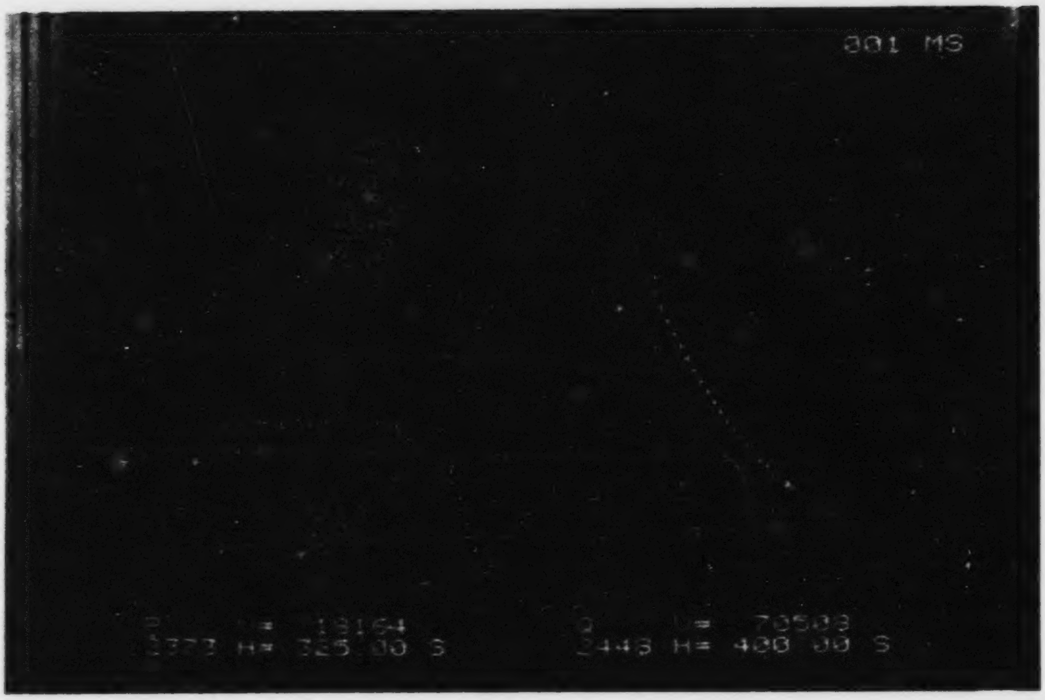

FIGURE 28: COMPARISON OF PRESSURE TRACES AT 1600 RPM AT RATED LOAD

TOP CURVE: 1990 DIESEL
BOTTOM CURVE: #2 DIESEL

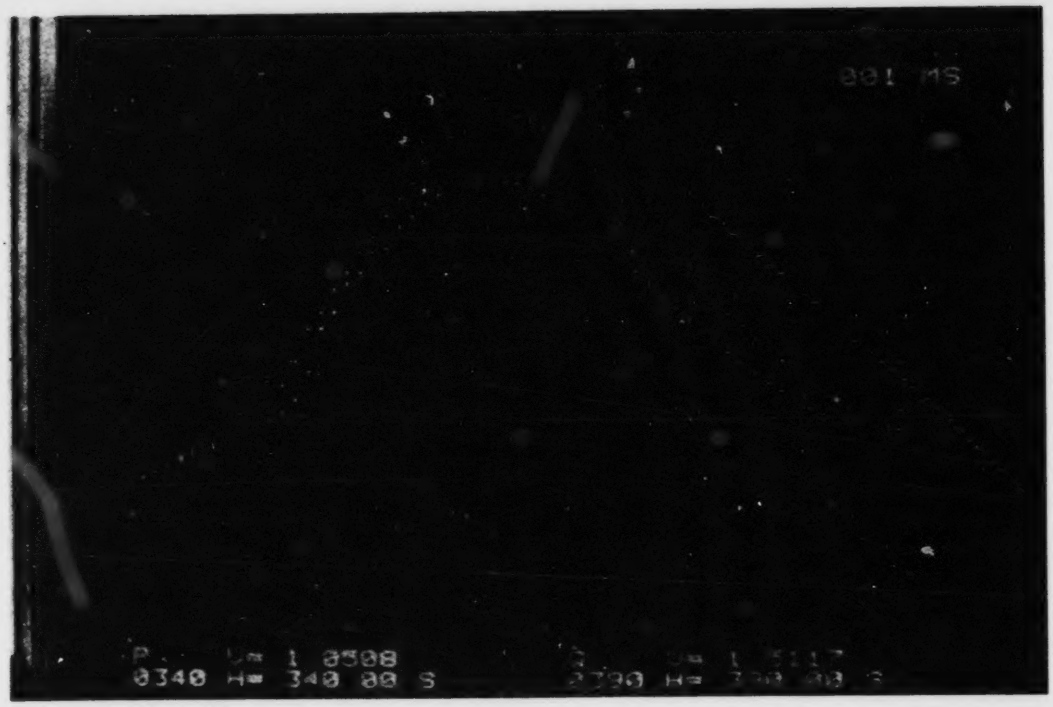

FIGURE 29: COMPARISON OF PRESSURE TRACES AT VARIOUS LOAD/SPEED SETTINGS

TOP CURVE: #2 DIESEL AT 2200 @ RATED LOAD
BOTTOM CURVE: #2 DIESEL AT 1800 RPM @ 150 FT. LBS. LOAD

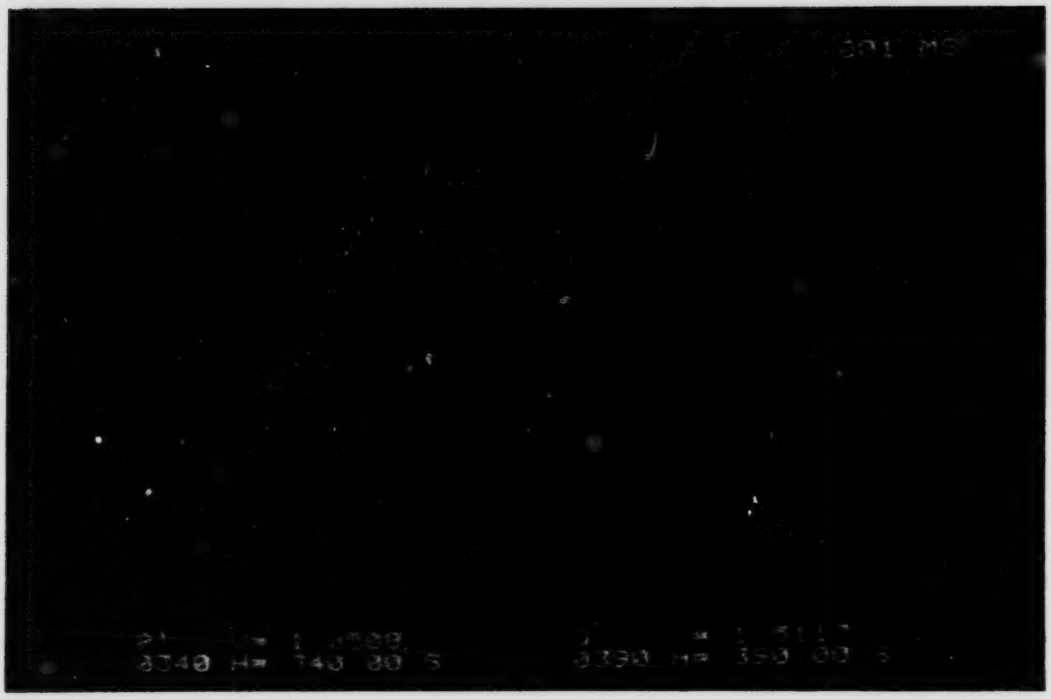

FIGURE 30: COMPARISON OF PRESSURE TRACES AT VARIOUS LOAD/SPEED SETTINGS

TOP CURVE: #2 DIESEL AT 2200 @ RATED LOAD
BOTTOM CURVE: #2 DIESEL AT IDLE CONDITION

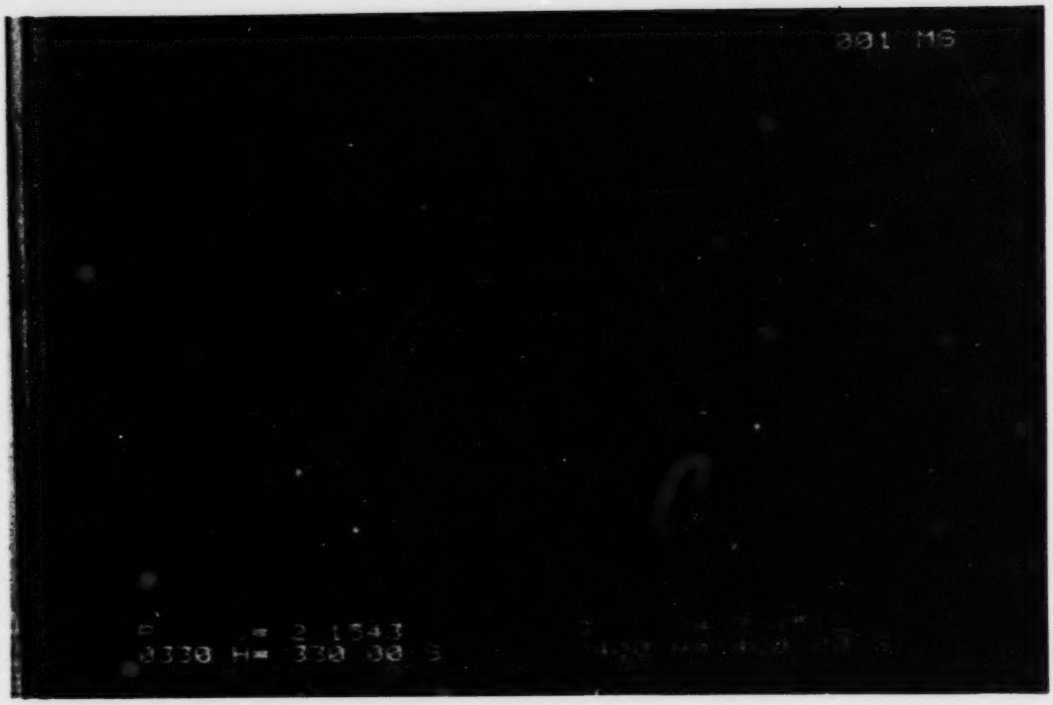

FIGURE 31: COMPARISON OF PRESSURE TRACES OF THE SAME FUEL AT VARIOUS LOAD/SPEED SETTINGS

TOP CURVE: #2 DIESEL + 15% MeOH AT 2200 RPM @ RATED LOAD

BOTTOM CURVE: #2 DIESEL + 15% MeOH AT IDLE CONDITION

FIGURE 32: COMPARISON OF PRESSURE TRACES OF THE SAME FUEL AT VARIOUS LOAD/SPEED SETTINGS

TOP CURVE: #2 DIESEL + 15% MeOH AT 2200 @ RATED LOAD
BOTTOM CURVE: #2 DIESEL + 15% MeOH AT 1800 @ 150 FT. LBS.

6.0 SUMMARY OF FUEL/ENGINE TEST RESULTS

6.1 ENGINE PERFORMANCE AND MAXIMUM HORSEPOWER

6.1.1 Diesel Fuels and Diesel Dalco Blends

Direct comparison of the torque curve and the maximum engine horsepower between fuels is complicated by the different heating values of the fuels and the difference in fuel weight delivered at each stroke since the fuels examined differed in density, calorific value and viscosity.

The #1 and #2 diesel fuel results were therefore taken as reference baselines for measuring the change in engine performance with fuel variations when no changes were made in the rack (fuel volume) settings to compensate for fuel changes: the results therefore do not represent the optimum (torque, horsepower, emissions) which might be obtained through optimization.

The torque curves for #1 diesel (sample #1), #1 diesel with 2.5 volume % Dalco (sample #13) and for #2 diesel (sample #18) all have the same shape, the differences in the observed torque values being due principally to differences in fuel mass delivered to the cylinders (the diesel fuels had the same 44.4-44.5 CCR cetane ratings and heats of combustion).

The torque values observed for the highly aromatic "1900 diesel" (CCR cetane rating 33.4, sample #22) were substantially different from the conventional #1 and #2 diesel fuels: the peak torque appeared at 1700 rpm with the 1990 fuel, compared to 1600 rpm for the conventional diesels. The mass of the "1900 diesel" fuel delivered per second was substantially higher than for the conventional fuels: the torque at maximum engine speed (and horsepower) was about 14% higher than for #1 diesel fuel, and the combustion characteristics were found to be even more different from those of #1 diesel fuel than many of the methanol- and water-diesel emulsions investigated.

6.1.2 Methanol Blends

The addition of methanol in 5% increments from the 5% (volume) to the 30% (volume) level to #1 diesel (with appropriate adjustments in Dalco content to provide stable emulsions) resulted in a smooth deterioration in measured torque values. The blend of 5% methanol in #1 diesel (with Dalco present) gave a torque curve almost identical to that without methanol, except at lowest engine speeds where the 3-component blend gave a 5% higher torque rating than the #1 diesel with Dalco. Higher levels of methanol in the blends reduced the torque and maximum horsepower in parallel with the reduced heating value of the oxygenated blends. As an illustration of the effect of methanol, we can compare the observed loss in the maximum horsepower of the engine with the loss in fuel heating value as follows:

	Level Methanol Addition	BTU Loss vs Diesel #1	HP Loss vs Diesel #2
Diesel #1 (with Dalco)	0%	0%	0%
Sample #2	5	1.6	0.8
Sample #3	10	3.7	2.7
Sample #4	15	5.9	4.4
Sample #5	20	7.7	9.8
Sample #6	25	11.1	12.5
Sample #7	30	14.6	14.5

The power loss at the 30% methanol addition level was significant at high speeds. It was concluded that methanol addition to #1 diesel fuel at the 15% level gave acceptable engine performance, at 20% adequate performance, but inadequate performance and high fuel consumption were observed at the 30% methanol level.

As expected, the addition of the cetane-enhancing additive iso-octyl nitrate at the 0.1 volume % level did not significantly change the torque curve of the 15%, 25% or 30% methanol blends with #1 diesel fuel. However, the low cetane levels of the methanol/diesel blends (CCR cetane ratings ranged from 44.1 for the 5% blends to 27.0 for the 25% methanol blend) would doubtless have affected cold start capability, but in the present tests this aspect of performance was not investigated.

The addition of iso-octyl nitrate to #2 diesel fuel-methanol blends gave significant torque increases at the 15% methanol addition level. The addition of iso-octyl nitrate ignition improver to a 15% methanol/Dalco/#2 diesel fuel emulsion increased the engine torque at all speeds, but especially at the maximum 2600 rpm. This effect is not due to the cetane enhancement that occurred, but rather to the change in viscosity of the emulsion, since an 8% higher mass of the multi-component fuel was delivered to the engine than when the additive was omitted (this increased mass effect was also noted with #1 diesel at the 25% methanol addition level, but not other levels). With this effect (using the cetane additive) operating, the engine performance was almost identical on #1 and #2 diesel fuels, but without the additive the #2 diesel 15% methanol blend gives marginal engine performance: fuel injection optimization is required.

6.1.3 Water Blends

The emulsification of 5% water into a #1 diesel fuel (using 2.5% Dalco, Sample #4) gave a dramatic deterioration in engine performance in the high speed range. At 2600 rpm, for example, a 25% reduction in torque was observed compared to that with #1 diesel (and Dalco) alone.

The torque reduction was greater than could be accounted for by the reduced heat content of the fuel. Addition of a small volume of organic nitrate ignition improver (0.15 weight % iso-octyl nitrate, sample #12) or of ammonium nitrate (0.5 weight %, sample #15) restored the torque values to those observed without water (the mass of fuel delivered being increased also). The performance of the cetane-enhanced 5% water blend was essentially the same (torque, horsepower at maximum load) as that shown by #1 diesel and #1 diesel with 5% methanol.

A 5 component-blend of #1 diesel with water (7.5 volume %), methanol (7.5 volume %) emulsified with Dalco (3%) brought to an acceptable cetane value by the addition of iso-octyl nitrate (0.2%) had acceptable performance. The torque values were almost indistinguishable from those of a #1 diesel-10% methanol blend and only somewhat inferior at low engine speeds to those from a cetane-improved #1 diesel, 5% water, 2.5% Dalco blend.

Further detailed investigation is merited of the trade-off between fuel economy and engine performance, since it appears from the present work that a more fuel-efficient combustion regime may be occurring when oxygenated species are incorporated (methanol, water). In particular, comparisons are required between the performance and fuel economy of blends of diesel with 10% methanol, 15% methanol and 7.5% methanol combined with 7.5% water. If cold-start (low cetane) problems are encountered with automotive diesels, the use of the blends in stationary diesels is still possible. The demonstrated use of ammonium nitrate as a cetane enhancer may provide a low cost means to overcome the low ignition quality of these oxygenated blends: See Figure 33.

6.2 Ignition Delay Results (See Section 5.5.2 for detailed results).

6.2.1 Ignition Delay in Base Diesel Fuels (Combustion Chamber Pressure Traces and CCR Cetane Values)

The tests with a warmed-up engine do not provide information on the critical cold-start performance of alternative fuels but that information can be inferred from the combustion tests and the CCR diesel cetane tests conducted by the Fuels and Lubricants Laboratory of the National Research Council.

The two reference diesel fuels gave essentially identical results by the CCR method with values at 44.4-44.5. The combustion test method permits a comparison of ignition delay across the engine speed spectrum: here only minor differences in ignition delay were observed between #1 and #2 diesel fuel. In contrast, the "1990 diesel" with a cetane value of 33.4 gave an unacceptable high level of ignition delay - the value for the change in pressure raise per crank angle degree being about 1.5 times that for the conventional fuels at all engine speeds. While the engine on the dynamometer test stand operated when warmed up without problems, the high ignition delay would certainly create performance problems in on-highway use of the low cetane fuel and problems of engine durability (as discussed later).

The addition of 2.5% of the highly aromatic Dalco to #1 diesel fuel gave an effect similar in direction but not in magnitude to that observed with the highly aromatic 1990 fuel. The effect of Dalco addition to

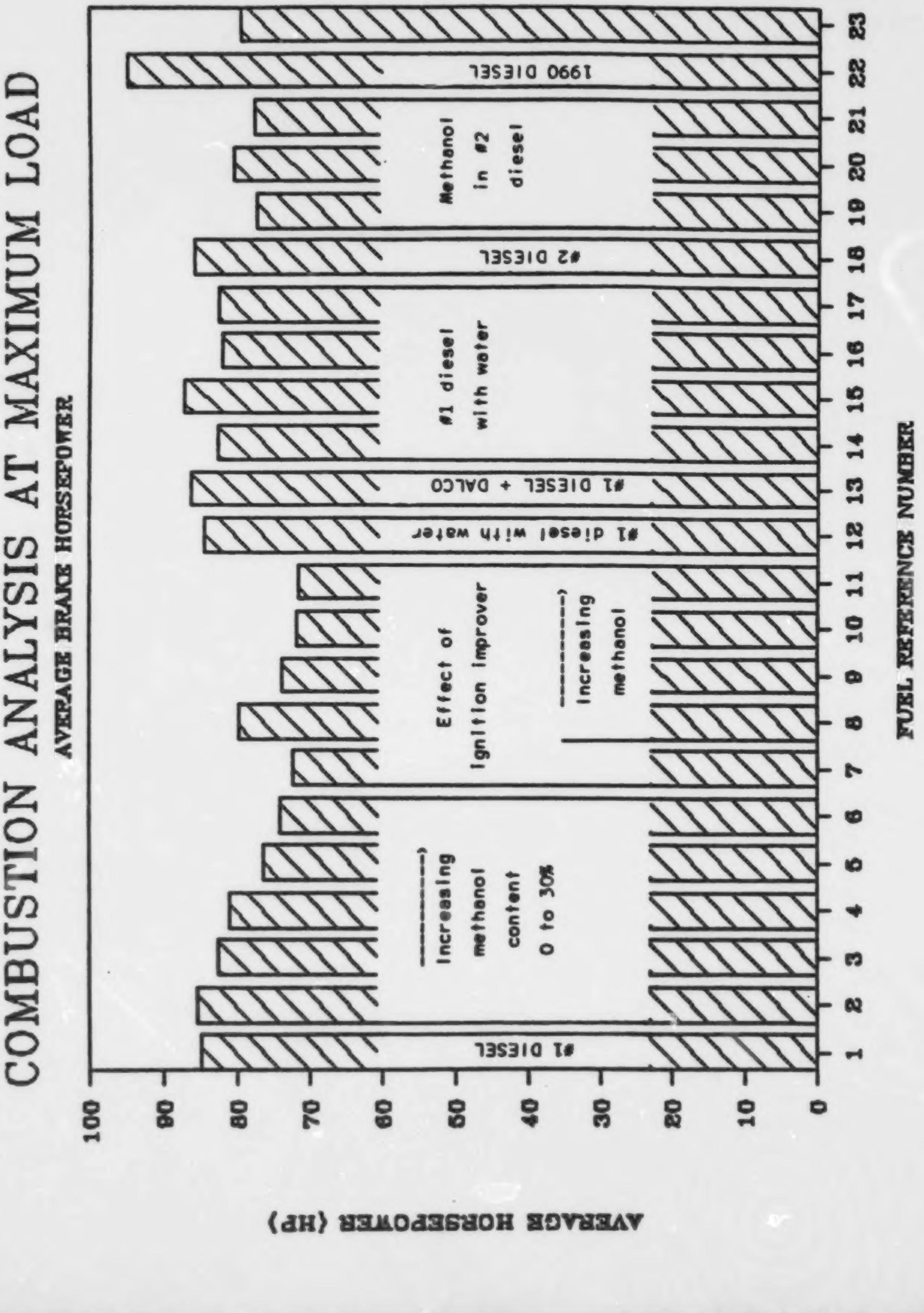

FIGURE 33: COMBUSTION ANALYSIS AT MAXIMUM LOAD

#1 diesel fuel was to change the CCR cetane value from 44.5 to 42.0, but the effect as measured by the trace of pressure rise in combustion tests was shown to be most severe at slow engine speed (1400 - 1500 rpm) and at the higher speeds (2400 - 2600 rpm, where the engine in the combustion tests operated under full load conditions). The iqnition delay at 1400 rpm was increased to 130% of that of the base diesel fuel.

6.2.2 Methanol Blends

The addition of methanol to the #1 diesel in 5% increments led to a steady decrease in the measured CCR cetane values from 44.1 with 5% methanol and 1.17% Dalco to 27.0 when 25% methanol and 5.8% Dalco were added. The CCR value for 30% methanol and 7% Dalco was very low (reported less than 30). The pressure rise measurements in the combustion tests also showed a progressive increase in ignition delay with these formulations, but surprisingly the 5% and 10% methanol additions (with Dalco used at 1.17% and 2.33% levels) gave ignition delay responses no worse than that for the #1 diesel with 2.5% Dalco - both being clearly superior to the 1990 diesel fuel.

At the 15% methanol, 3.5% Dalco level (CCR cetane rating 37.0) unsatisfactory ignition delays were observed, with values at all engine speeds being about the same as for the 1990 diesel, especially at the 1400 rpm and 2600 rpm conditions. Without an additive to reduce ignition delay, 10% methanol would appear to be the limit for on-road engine performance. At 30% methanol addition (sample #7 which also has 7% of the Dalco reagent) a disastrous degradation of fuel quality is observed with reference to ignition delay. This could be ameliorated by the addition of organic nitrate ignition improvers, but in the combustion tests the addition of up to 0.4% of iso-octyl nitrate (sample #11, CCR cetane value 31.9) did not provide satisfactory ignition improvement. The addition of iso-octyl nitrate (0.1%) to the 15% methanol 1.17% Dalco emulsion in #1 diesel fuel gave acceptable ignition timing: the 40.8 CCR cetane value fuel was clearly superior to the 1990 diesel fuel and equal in ignition delay to the #1 diesel, 10% methanol, 2.33% Dalco at all engine speeds.

The response of the ignition quality of #2 diesel fuel to methanol addition differed from that with #1 diesel fuel, especially in the critical low engine speed range where the ignition delay was longer (worse) than for the 1990 diesel fuel analogue (sample #8, 15% methanol, 3.5% Dalco, 1% ignition improver) at engine speeds greater than 1600 rpm, even when the ignition improver level was increased (by 50% to 0.15% iso-octyl nitrate). It is clear that, in the methanol-diesel blends, operation at the 15% methanol level requires ignition improver, the exact level of which will be determined by the response of the base diesel fuel used. It is also clear that improvements in ignition quality will occur when lower quantities of Dalco can be used in the formulations.

6.2.3 Water Blends

Turning now to the blends with water, we find a different ignition delay response than with methanol. Addition of 5% water to the #1 diesel 2.5% Dalco blend (sample #14 compared to sample #13) gave an apparent reduction in ignition delay with water at low engine speeds (up to 2000 rpm) and an increase in ignition delay at speeds from 2200 to 2600 rpm. This may account for the preciptious drop in torque observed (sample #14) with water addition without cetane adjustment. With a conventional cetane improver (sample #12, 0.15% iso-octyl nitrate) or the new inorganic cetane improver ammonium nitrate (sample #15 made possible by the presence of water in the blend) measured ignition delays were somewhat less than with #1 diesel and Dalco alone (sample #13). Ammonium nitrate at the 0.5% level appears to be superior to the organic nitrate at the 0.15% level in reducing ignition delay in the 5% water addition range. The addition of barium acetate (a potential exhaust speeds above 1600 rpm (but not at idle). The cetane-improved 5% water compositions appear to have satisfactory ignition quality. The ignition delay for highly-oxygenated water blends (15% methanol with 2.5% water, plus Dalco and 7.5% methanol, 7.5% water with Dalco) - even with the organic ignition improver iso-octyl nitrate used - is unsatisfactory, particularly at the low engine speed condition - with ignition delays 30% greater than for the cetane-improved 5% water-in-diesel fuel blends (such as sample #12): See Figure 34.

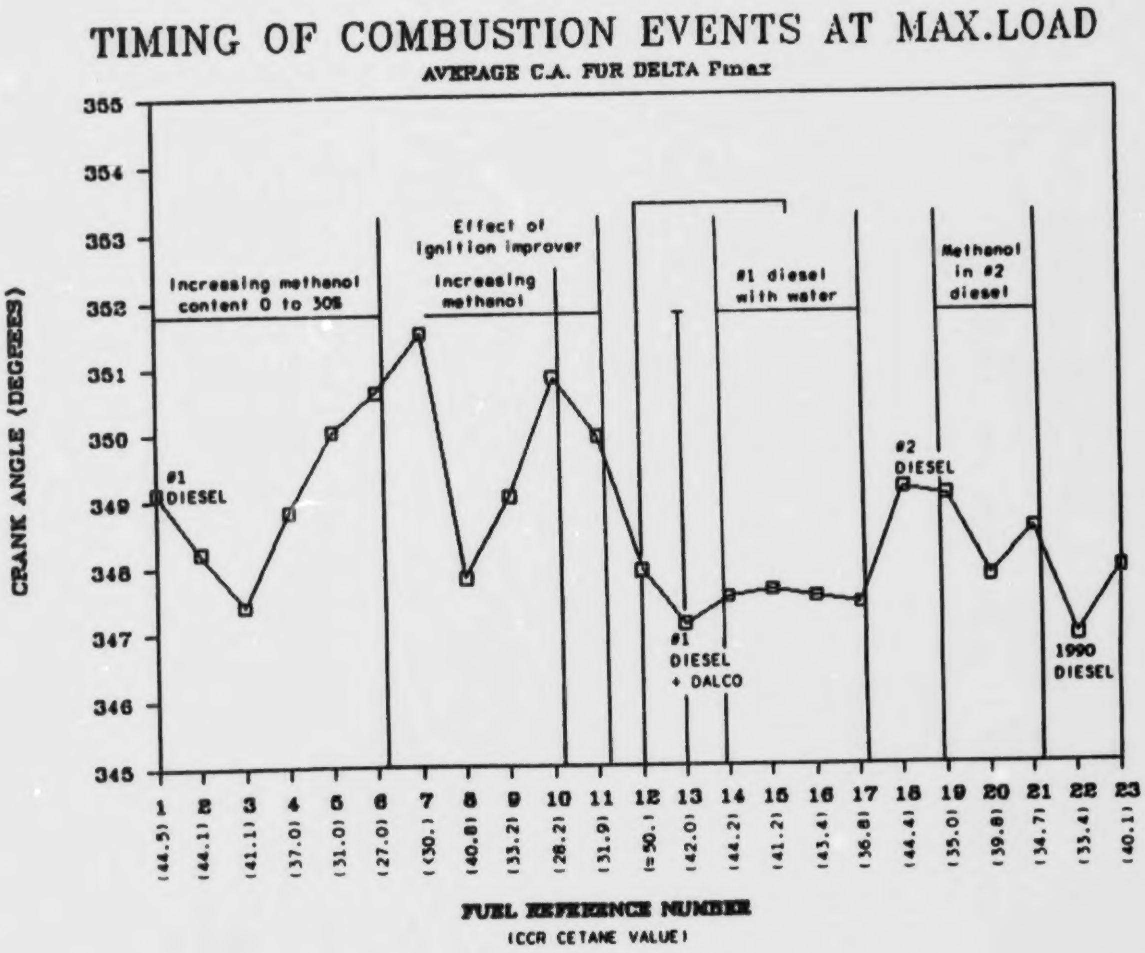

FIGURE 34: TIMING OF COMBUSTION EVENTS AT MAX. LOAD

6.3 MAXIMUM CYLINDER PRESSURE MEASUREMENTS

6.3.1 Diesel Fuel Baseline

In addition to the ignition delay of a fuel, engine manufacturers are interested in the maximum absolute pressure achieved, since engine life is influenced by the frequency and magnitude of excursions above maximum pressure rating for the engine (and also by the rate of pressure rise).

The effect of fuel change on pressure is well illustrated by comparing the maximum pressure for the "1990 diesel fuel" (sample #22) with those for #1 and #2 diesel fuel (samples #1 and #18). It must be noted that the maximum pressure recorded is dependent on the mass of fuel combusted, the combustion process (ignition timing, flame speed), and the chemical composition of the combustion products. Satisfactory pressure (less than 10% increase above #1 diesel fuel) was observed for all oxygenated fuels. Only the 1990 diesel appeared to present problems. At the 2600 rpm full load condition the maximum cylinder pressure recorded for the 1990 diesel sample was almost 20% higher than that for #1 diesel. The change in the combustion process with water addition to #1 diesel fuel is illustrated by the change in Pmax which occurs at low engine speeds (1600 rpm) with water but at maximum speed with all hydrocarbon and diesel-methanol blends.

The conclusions: use of oxygenated fuels is not expected to lead to peak cylinder pressures which would necessitate changes in cylinder and in-cylinder component design. The use of the 1990 diesel fuel may seriously affect engine durability (as related to the importance of maximum pressure excursions above those observed with conventional diesel fuels).

Figure 35 illustrates the effect of changing fuels on the average of the maximum cylinder pressures recorded for each combustion test condition. The figure illustrates that the average of the peak cylinder pressures is somewhat higher for the alternative fuels than for #1 diesel and that for the 1990 diesel fuel substantially higher. However, the figure should not be strictly interpreted to measure engine durability: that will be dependent, as discussed above, more to the frequency of the highest pressure excursions which occur at the maximum engine power. With the exception of the 1990 diesel fuel, this factor is not significantly different for the blends.

The variation in the speed of fuel/air combustion is illustrated in Figure 36. Here the effect of ignition delay and flame speed are combined. In general, the addition of methanol and ignition improvers both reduce the time for cylinder pressure to reach its maximum showing the competing processes involved (increased flame speed for methanol, reduced ignition delay with ignition improvers). The system characterizes #2 diesel fuel as the slowest burning

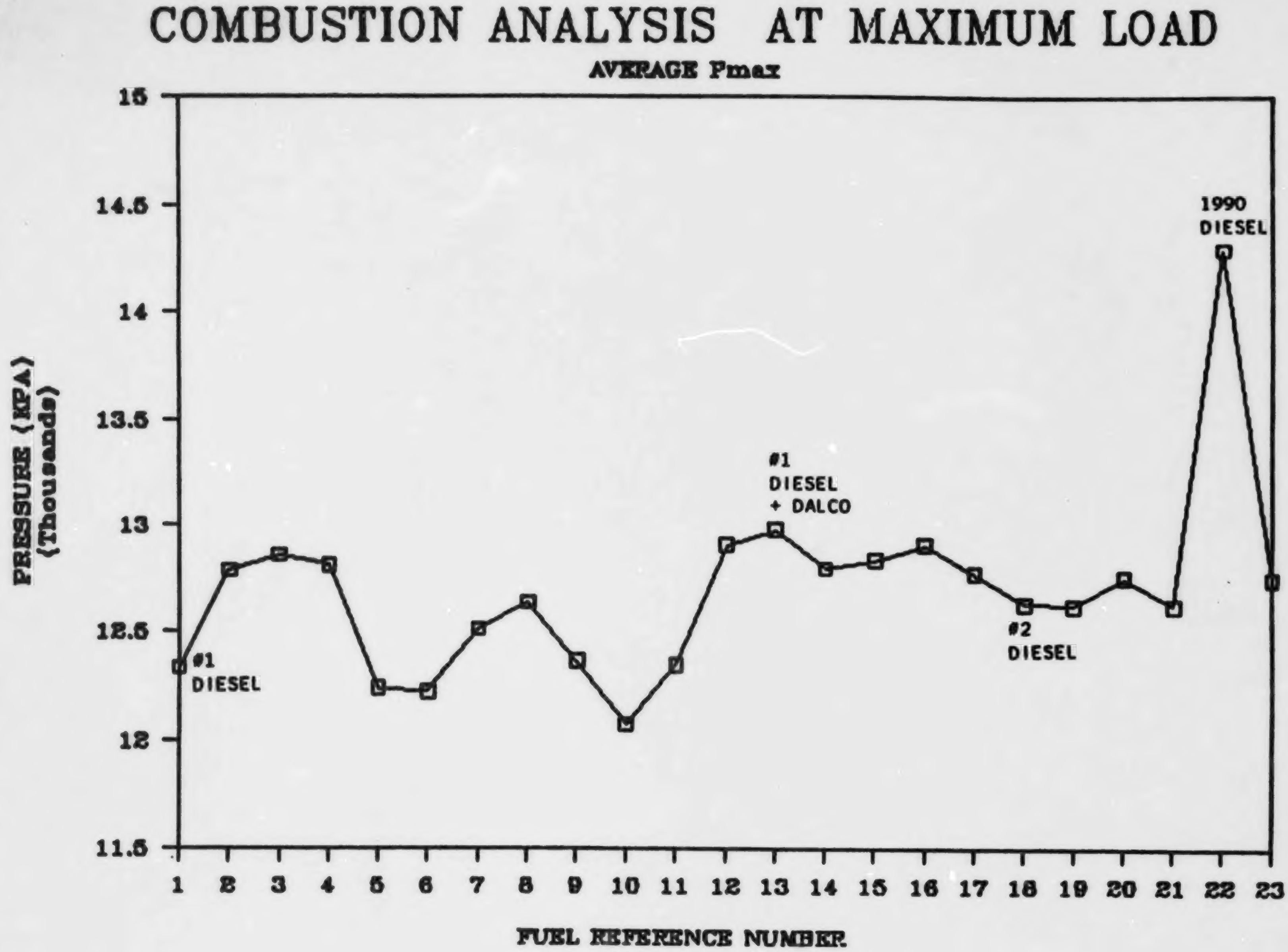

FIGURE 35: COMBUSTION ANALYSIS AT MAXIMUM LOAD

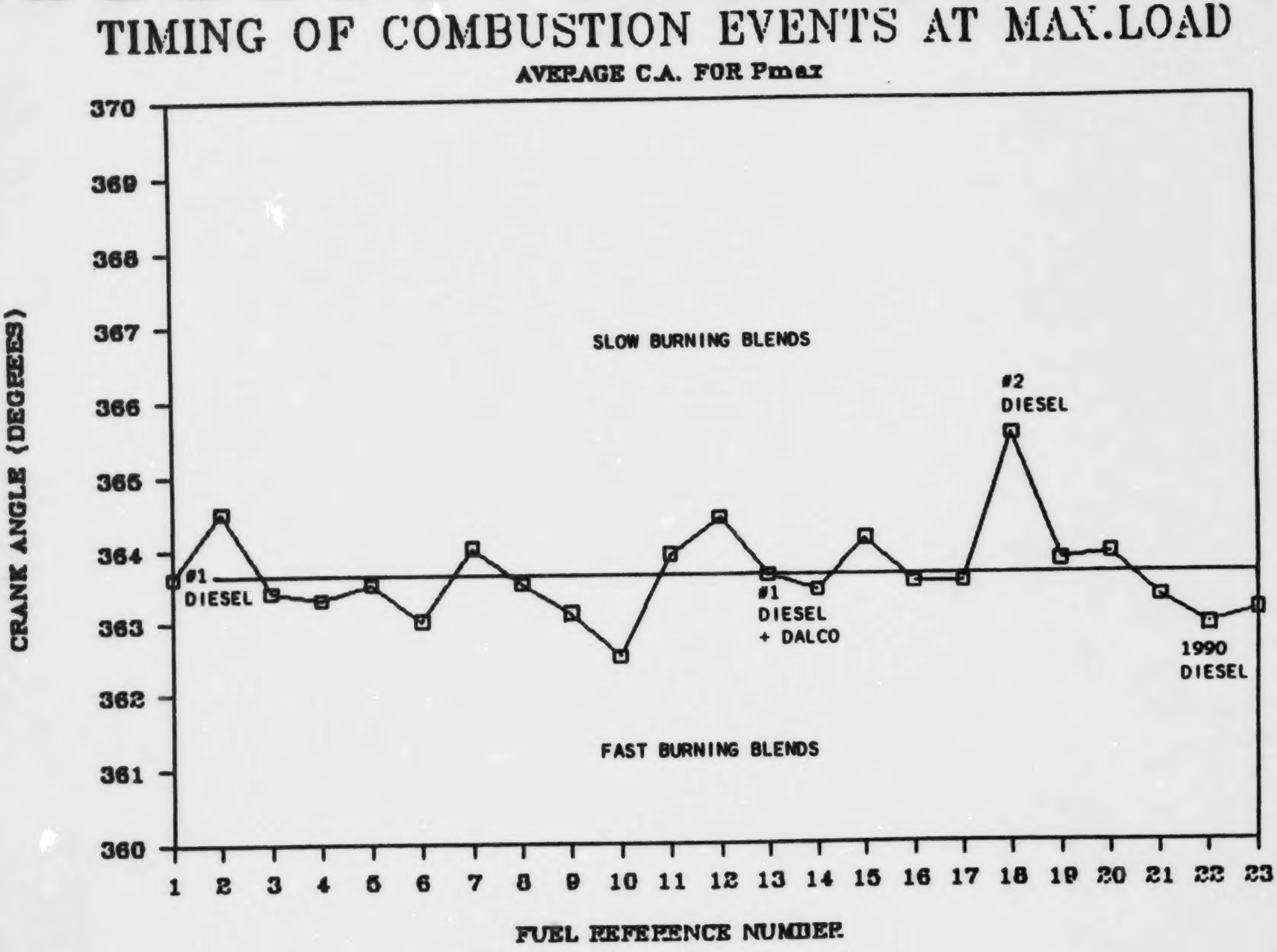

FIGURE 36: TIMING OF COMBUSTION EVENTS AT MAX. LOAD

of the fuels examined, the 1990 diesel and a cetane-fortified 30% methanol in #1 diesel fuel as the fastest burning fuels.

6.4 EXHAUST EMISSIONS

The combustion tests were not conducted using a reproduceable internationally-recognized procedure, such as the 13 mode EPA, but nonetheless useful comparative data on emissions was collected at each engine setting which can be used to identify comparative trends among the different fuels and anomalies.

6.4.1 Particulates

The steady state test procedure gave comparative values for the total level of particulates and for the soluble and insoluble particulates emitted at each engine setting and fuel. The values obtained cannot be compared with the values established by the (US) EPA for heavy-duty trucks and buses over the EPA cycle which includes measurement of transient emissions and are:

1988 EPA standard:	0.6 g particulates per brake horsepower hour (BHPH)
1991 EPA standard:	0.1 g particulates per BHPH for buses, 0.25 for trucks
1994 EPA standard:	0.1 g particulates per BHPH for buses and trucks

Note that current buses in use produce about 0.55 g particulates per BHPH with #1 diesel fuel, the GM methanol bus about 0.17 g (steady state), whereas the spark-ignition methanol buses from M.A.N. produce about an order of magnitude lower total particulates.

In the present analysis, variations with respect to #1 diesel performance in the test engine are reviewed on a comparative basis.

#1 diesel fuel gave the lowest level of particulates of all the fuels tested at idle but the values for #2 diesel, for Dalco blended with #1 diesel and for #2 diesel-methanol-Dalco blends (15% and 20% methanol, samples #19 and #21) were close. Addition of methanol to #1 diesel fuel increased the total particulates steadily until with 30% methanol a fourfold increase in particulates was measured, compared to #1 diesel fuel (with or without Dalco). The addition of 5% water to #1 diesel (with and without the use of the organic nitrate) also increased the total particulates emitted at idle to somewhat greater levels than a 5% methanol addition. The 1990 fuel gave the highest particulate count at idle.

With engine speeds and loads ranging from 1400 to 2200 rpm and 25% to 100% load, the emission behaviour varied in such a way that a detailed analysis and more data will be required to provide statistically significant data. The trends appear to be:

- Except at idle the addition of methanol to #1 and #2 diesel fuel does not increase the total particulates.

- The level of methanol addition also seems not to be important.
- The cetane-improved methanol #1 diesel blends (sample #'s 8,9,10,11) showed a higher level of total particulates than the clear (unimproved for cetane) blends (this effect was not shown by #2 diesel-methanol blends).
- Under most test conditions the 5% water blend without cetane improver gave lower levels of total particulates than the methanol-diesel blends but again the addition of the organic ignition improver iso-octyl nitrate in general increased the particulate emissions compared to the clear fuel (unimproved for cetane).

The total particulate level of the barium acetate-containing emulsion (sample #16 designed to reduce visible black smoke) was not significantly greater than that of a control (sample #12) without added barium salt. Work at other laboratories using deliberate addition of manganese, lead and other naphthenates (salts of an oil-soluble organic acid, naphthenic acid) have shown that the metals, typically in the form of oxides or sulphides, are retained on similar exhaust gas filters and this indicates that the major portion of the particulate from barium acetate may be the added barium salt in the fuel.

The evidence on the reduced level of carbon-containing particulates from use of barium acetate solution comes from an examination of the soluble particulates levels in the exhaust and the filter deposits. Both the total level of solubles and the the proportion of soluble particulates in the emission are exceptionally low for operation with the barium-containing fuel at all conditions other than idle. The filter which collected the mostly insoluble particulates was light in colour, indicating no accumulation of graphitic carbon (See Figure 37).

We conclude that the total organic particulates are therefore substantially reduced by barium salt addition to a diesel/water emulsion. Other oil-soluble salts, including barium and manganese derivatives, have previously been reported to reduce the level of organic particulates (and to increase the solvent-soluble proportion of the particulates). The diesel-water emulsions may provide a convenient means to carry the metal-derived particulate modifiers.

The addition of methanol to the hydrocarbon fuels increased the soluble proportion of the particulates mostly in a linear way. The cetane-improved methanol blends had an even higher proportion of solubles in the particulates collected than the blends without iso-octyl nitrate. The proportion of solubles in the particulate from methanol diesel blends (but not water-diesel emulsions) increased at idle and was lowest at full load and 1600 rpm. However, no further correlation with engine conditions or fuel properties was possible.

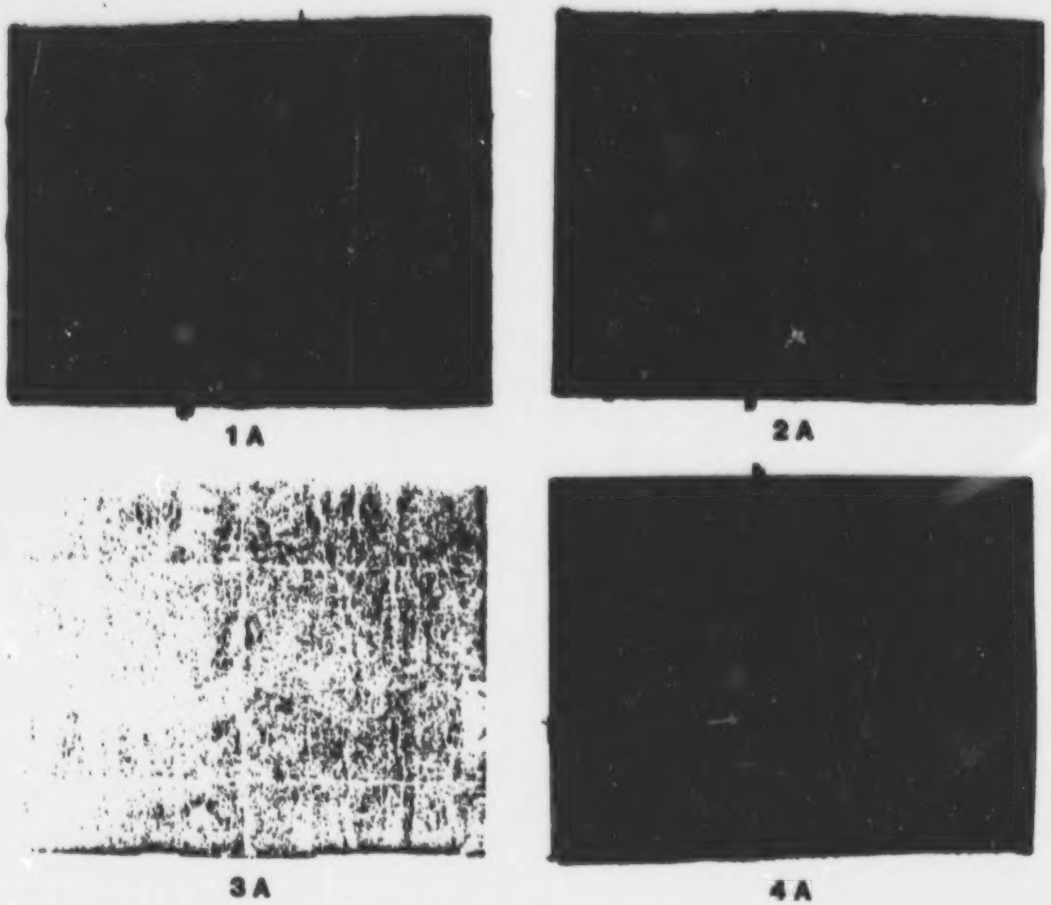

FIGURE 37: APPEARANCE OF EMISSION FILTERS

1A - #1 NEAT DIESEL - 1600 RPM 100% LOAD
2A - #1 DIESEL + 5% M20 + 2.5% DALCO + 0.15% DII - 1600 RPM 100% LOAD
3A - #1 DIESEL + 5% H20 + 2.5% DALCO + 0.15% DII + BARIUM ACETATE
4A - 1990 DIESEL - 1600 RPM 100% LOAD

6.4.2 NOx Emissions

The control of emissions of nitrogen oxides (NOx) from diesel engines will be strictly controlled in North America in the future. EPA standards for heavy-duty engines will be 6.0 grams per BHPH in 1988, somewhat lower (5.0 g/BHPH) in 1991: Canada's standards will be similar. As with particulates, the gaseous nitrogen oxide emissions contain two species, one of which (the nitrogen dioxide component) is considered to be more toxic than the more inert companion nitrogen monoxide (frequently termed "nitrogen oxide").

The trends observed in NOx emission are that at idle and part load conditions stepwise increases in methanol content of diesel-methanol blends were accompanied by similar decreases in NOx emissions. The NOx was increased by the presence of the organic nitrate iso-octyl nitrate and by water addition, but not linearly.

The trend in reduced in NOx emissions with methanol addition was not observed in tests with the engine run at maximum load (1600 rpm and 2200 rpm conditions): at high speed and full load the addition of methanol increased the NOx emissions: at medium speed and part load an intermediate (no response) condition prevailed. We do not know the actual temperatures reached under these combustion conditions where high combustion temperatures are known to be the cause of NOx production.

Interesting results were observed in the case where ammonium nitrate was used to reduce ignition delay (sample #15). This blend gave an unexceptional level of NOx emissions, despite the high level of nitrate and ammonium ions present. The thermal decomposition of ammonium nitrate to nitrogen oxides must be accompanied by reduction of the nitrogen oxides to elemental nitrogen. A similar result with organic nitrates used in alcohol formulations in diesel engines has been reported by Daimler-Benz.

Another unanticipated result is the high level of NOx produced when 5% water is used with diesel fuel under idle conditions. This impediment was not sustained when the engine was operated at 1400-2200 rpm at varying loads. It was previously believed that water addition would reduce the peak combustion temperature and therefore reduce NOx, as has been demonstrated in diesel-fueled power turbines.

The differences between the levels of nitric oxide and nitrogen dioxide produced by the different fuels and at different engine settings were complex. In general, the weight of the nitrogen dioxide produced per BHPH was about one half of the nitric oxide level at all conditions except idle, where the weights per BHPH were about the same. At idle and low speeds and low load conditions addition of methanol to #1 diesel greatly reduced nitric oxide formation but had no effect on the nitrogen dioxide level. Outside the idle and low speed, low load range, in general no great variations occurred in the relative proportions of the two oxides or the total level of NOx when fuels and engine conditions were varied. However, a more rigorous analysis of the emission data might provide new correlations.

In summary: The test engine produced NOx levels under all conditions which substantially exceeded the 1988 EPA standard of 6.0 g of NOx per BHPH. Except at idle and low load, low speed operations, the NOx levels were unaffected by the addition of methanol to diesel fuel. At idle and low load significant reductions in NOx output compared to #1 diesel fuel were observed only at high levels of methanol use (20%E methanol). Methanol addition is therefore not indicated as a means to reduce NOx in the given test engine.

The addition of water is also not a means to reduce NOx levels in the given engine: in fact, formulations containing water may also require other additives to overcome the exceptionally high NOx output observed when the engine was operated at idle.

6.4.3 Carbon Monoxide and Unburnt Hydrocarbon Emissions

Carbon Monoxide

The level of carbon monoxide emitted by the oxygenated fuel blends was, in general, somewhat higher than that for the diesel fuels alone and varied significantly in the tests with changes in engine speed and load and with fuel composition. The weight of carbon monoxide emitted per BHPH was lowest for all fuels at the medium speed and load condition (1800 rpm, 75% load), which increased 3-4 fold when changed to the high speed maximum load condition (except for the high level at both speeds exhibited by the 1990 diesel fuel and diesel #2 with 15% methanol, (sample #19) and by two orders of magnitude at the engine idle setting.

The level of carbon monoxide emitted at idle and a low speed, low load condition (1400 rpm, 25% load) increased linearly with methanol content: the #1 diesel with 30% methanol added (Sample #7) being exceptionally high. However, at higher speeds and loads (1800 rpm 75% load, 2200 rpm 100% load) there were insignificant variations in carbon monoxide output per BHPH among the methanol #1 disel blends. The emissions at the intermediate speed full load condition (1600 rpm, 100% load) showed a linear decrease in carbon monoxide with methanol addition and an increase when cetane improvers were added to the diesel methanol fuel blends.

The effect of water addition to diesel fuel was similar to that for methanol (at the 5% oxygenate level).

Unburnt Hydrocarbon

The level of unburnt hydrocarbon produced by the oxygenated fuels was, in general, equivalent to that produced from combustion of the base diesel fuels. Except at idle and low load test engine conditions, the unburnt hydrocarbon levels were close to the 1988 EPA standard of 1.3 g per BHPH. As with carbon monoxide emissions, the unburnt hydrocarbon emissions were high at idle and decreased by more than an order of magnitude with the change to the 1400 rpm light load setting, but essentially plateaued at higher speeds and loads.

The effect of methanol addition to #1 diesel fuel was to increase the unburnt hydrocarbon level in operation at idle and at low speed, low load, but at higher engine speeds and load the level of unburnt hydrocarbon did not correspond to the methanol level - it plateaued from 5% to 25% methanol addition with #1 diesel blends. At high speeds and loads the unburnt hydrocarbon from #2 diesel methanol blends differed from that with #1 diesel fuel blends, the reason for this is unknown.

The addition of water to diesel fuel in general gave lower levels of unburnt hydrocarbon under all test conditions but idle (where the unburnt hydrocarbon levels with and without water were similar).

Carbon Monoxide/Unburnt Hydrocarbon Comparison

When alcohol-containing fuels were tested at the idle and low speed engine conditions, the measured emission of carbon monoxide was substantially greater than that of hydrocarbon: this situation was reversed under high speed, high load engine operations when hydrocarbon emissions predominated, except for the unusual behaviour of the very low cetane fuels: 1990 diesel (sample #22) and #2 diesel with 15% methanol without cetane improver (sample #19).

In conclusion: the level of carbon monoxide emissions at low speed and idle conditions would not appear to present a problem, except at high methanol loadings with fuel blends which do not contain ignition improvers. Under other conditions and in fuels containing water, no excessive production of carbon monoxide was observed. The unburnt hydrocarbon levels of the oxygenated blends were acceptable compared to conventional fuels and essentially close to or within EPA requirements, except for a diesel/30% methanol blend without ignition improver which gave an unacceptable level of unburnt hydrocarbon (and carbon monoxide too) at idle.

6.5 FUEL CONSUMPTION

The heat of combustion of the oxygenated fuels varied from 84.5% to 98.4% of that of the #1 and #2 diesel reference standards, and comparison of the efficiency of the various fuels can only be made on the basis of the energy consumed in a unit time or in the performance of a given unit of work. Two comparisons are presented here:

a) a comparison of the energy consumed at idle by diesel and the various diesel blends.

b) a comparison of the energy consumed per BHPH at 2200 rpm, full load and at 1600 rpm, full load with #1 diesel fuel to the energy consumption with the blended oxygenated fuels.

Idle Condition (See Table 24 and Figure 38)

The energy consumed at idle by all fuels containing oxygen was substantially higher than for the two diesel fuels (the recorded result with the #2 diesel 30% methanol blend sample #19 may be in error). It appears that the energy loss is related to the proportion of methanol in the fuel, the greatest loss being exhibited by a 25% methanol in #1 diesel blend. Similar high energy consumption was shown by fuels formulated with water and the 1990 fuel.

The increased energy consumption of the methanol blends correlates with the increase in unburnt hydrocarbon and carbon monoxide noted at idle with these blends. The 1990 diesel fuel showed an exceptionally low efficiency at the idle condition: blends with oxygenates were superior to this fuel at idle.

2200 rpm/Full Load Condition (See Table 25 and Figure 39)

The energy consumption of the methanol blends with or without ignition improver measured with the engine operated at the 2200 rpm, full load condition, was higher than that of #1 and #2 diesel fuel but substantially improved over the low efficiency exhibited at idle. Two of the diesel-water blends (sample #'s 14 and 15) showed some reduced energy consumption under this condition (maximum torque position), but others were less efficient.

Sample #	Description	% Energy Used Per Second Compared to # Diesel	% BTU/lb of #1 Diesel
1	D #1 (#1 diesel)	100	100.0
2	D #1 + 5% methanol	Not measured	98.4
3	D #1 + 10% methanol	114	96.3
4	D #1 + 15% methanol	122	94.1
5	D #1 + 20% methanol	120	92.3
6	D #1 + 25% methanol	116	88.9
7	D #1 + 30% methanol	Not measured	85.5
8	D #1 + 15% methanol + DII	119	93.4
9	D #1 + 25% methanol + DII	142	87.7
10	D #1 + 30% methanol + DII (.2)	123	84.5
11	D #1 + 30% methanol + DII (.4)	109	84.9
12	D #1 + 5% water	123	93.2 calc*
13	D #1 + Dalco	132	99.5 calc*
14	D #1 + Dalco + 5% water	141	93.4
15	D #1 + Dalco + 5.5% water	Not measured	93.1 calc*
16	D #1 + Dalco + 2.5% water + DII	Not measured	93.2 calc*
17	D #1 + Dalco + 7.5% water + 7.5% methanol	138	87.3
18	D #2 (#2 diesel)	100	99.8
19	D #2 + 15% methanol	90	94.3
20	D #2 + 15% methanol + DII	128	93.9
21	D #2 + 20% methanol + DII	120	90.7
22	1990 fuel	167	96.5
23	D #2 + 15% methanol + 2.5% water + DII	Not measured	90.3

Note: DII - ignition improver
calc* - is calculated value, others measured.

TABLE 24: COMPARATIVE ENERGY CONSUMPTION AT IDLE
(FUEL CONSUMPTION AS % OF #1 DIESEL FUEL)

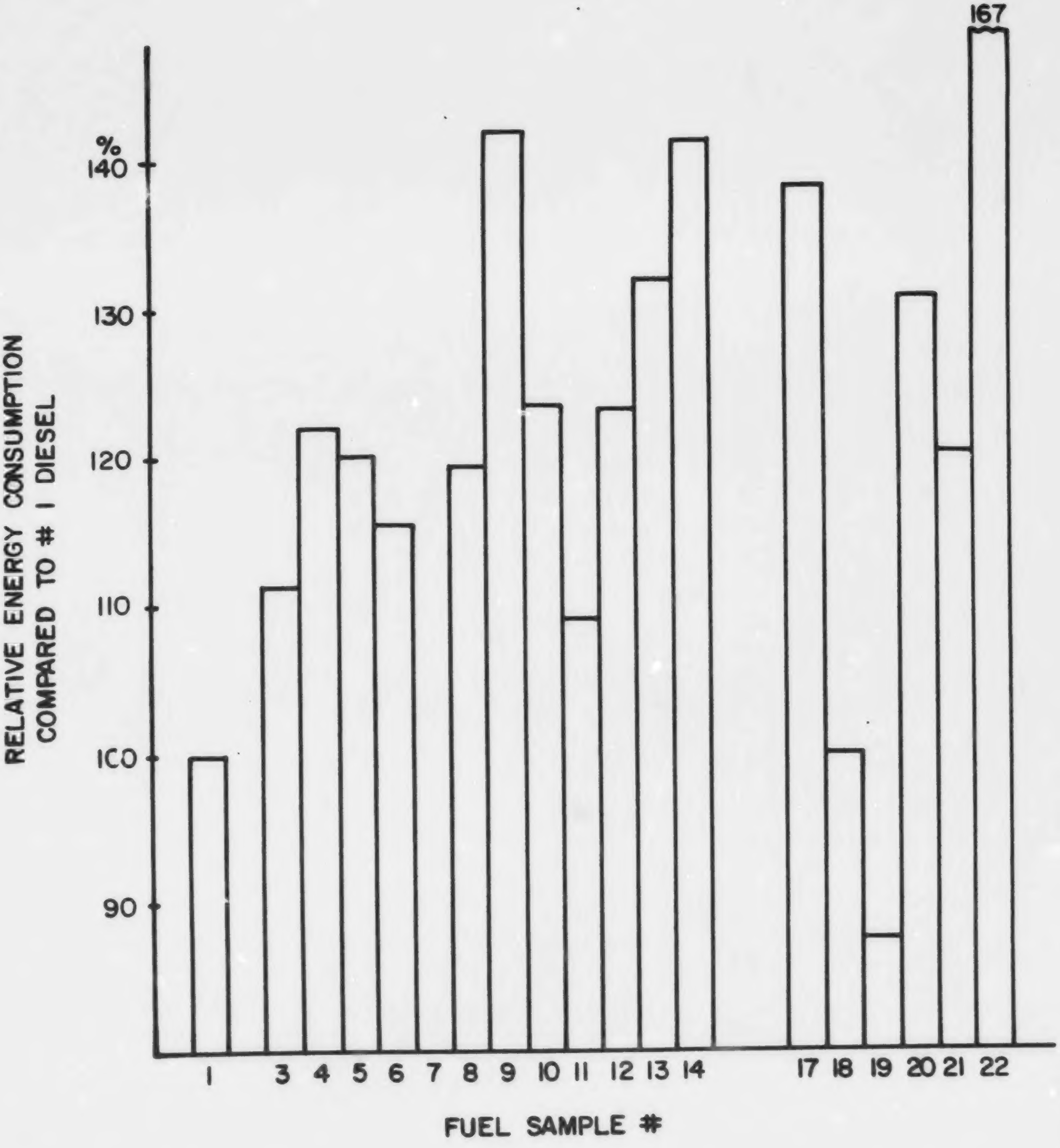

FIGURE 38: COMPARATIVE ENERGY CONSUMPTION AT IDLE RELATIVE TO #1 DIESEL BASELINE

Fuel #	2200 RPM Full Load	1600 RPM Full Load	% BTU of #1 Diesel
1	100.0	100.0	100.0
2	-	-	98.4
3	102.7	94.7	96.3
4	104.5	94.4	94.1
5	106.9	96.5	92.3
6	104.5	94.9	88.9
7	-	-	85.5
8	106.4	95.5	93.4
9	105.2	95.6	87.7
10	106.5	94.7	84.5
11	106.0	94.7	84.9
12	109.2	81.5	93.2 (calculated)
13	89.4	92.8	95.5 (calculated)
14	97.0	88.0	93.4
15	97.3	86.8	93.1 (calculated)
16	-	-	93.2 (calculated)
17	104.1	80.4	87.3 (calculated)
18	99.8	98.4	99.8
19	105.0	95.3	94.3
20	102.9	90.9	93.9
21	103.3	102.9	90.7
22	100.3	93.4	96.5
23	-	-	90.3

TABLE 25: COMPARATIVE FUEL ECONOMY MEASUREMENTS BTU/BHPH FOR FUEL VS #1 DIESEL

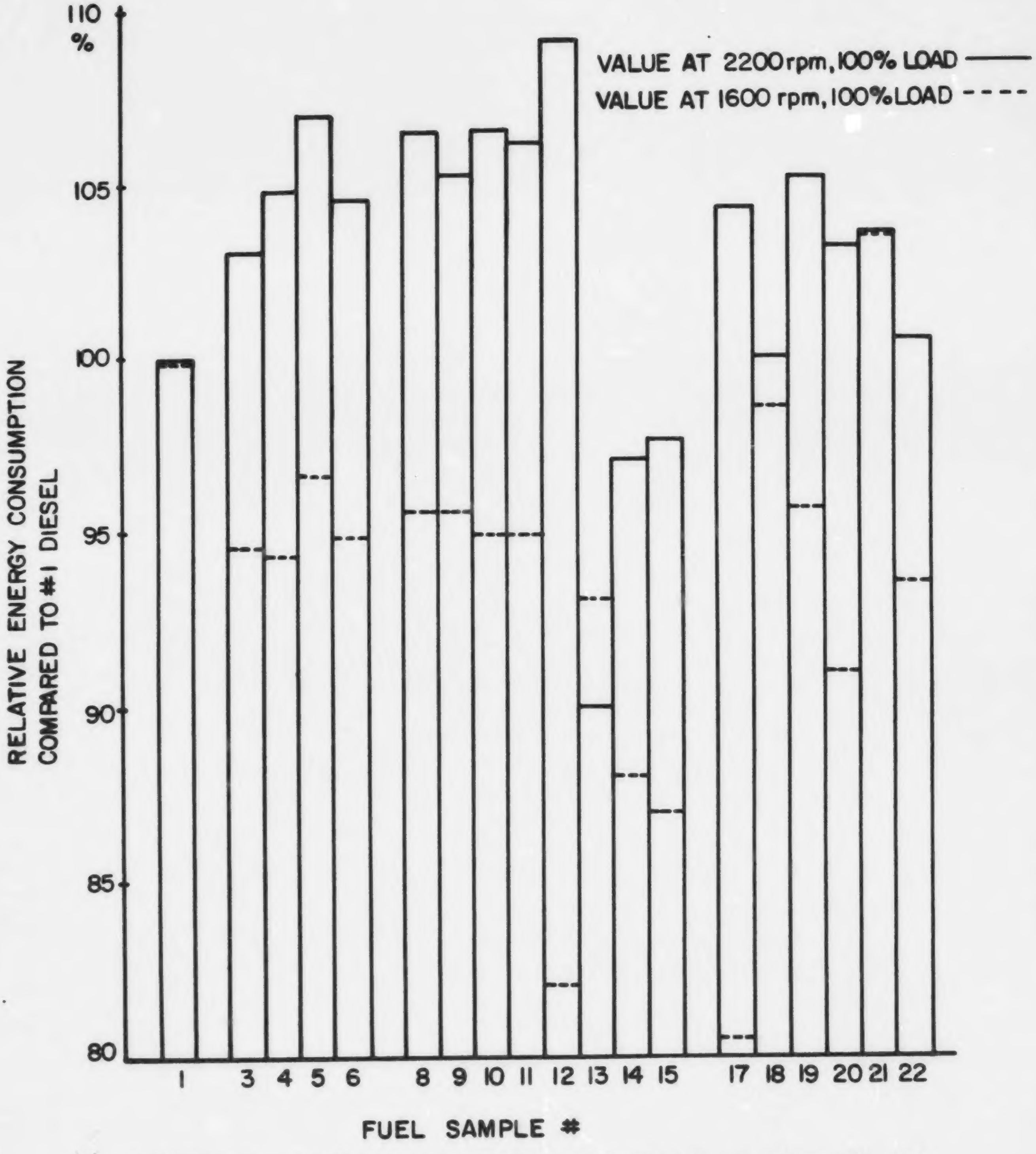

FIGURE 39: COMPARATIVE ENERGY CONSUMPTION AT 2200 RPM AND 1600 RPM, 100% LOAD: RELATIVE TO #1 DIESEL

1600 rpm/Full Load Condition

All blends (with the exception of a #2 diesel fuel 20% methanol blend, sample #21) exhibited a lower energy consumption under the 1600 rpm engine operating condition than #1 diesel fuel. Fuels with particularly outstanding fuel economy were those containing water which gave energy consumption values ranging from only 81% to 88% of those exhibited by #1 diesel fuel: the highest level oxygenated blend (containing 7.5% methanol and 7.5% volume water) gave the lowest energy consumption under the 1600 rpm engine regime.

The energy economy of the methanol blends in #1 diesel were all very similar across methanol content range 10%-30%, but variations occurred with the methanol in #2 diesel blends.

The 1990 diesel showed a substantial energy economy over #1 diesel fuel under this 1600 rpm condition.

The reasons for the improved energy efficiency of oxygenated and the 1990 diesel fuel with respect to the conventional diesels under the 1600 rpm full load condition, but not under idle and high rpm conditions, is unknown.

6.6 FUEL SELECTION FOR BEST COMPROMISE IN PERFORMANCE, ENERGY ECONOMY AND EMISSIONS

Table 26 summarizes the test results for each fuel and provides an opportunity for preliminary overall assessment (ranking) of the series of fuels.

FUEL SAMPLE #	ENERGY ECONOMY	EMISSIONS				PERFORMANCE IN ENGINE				OVERALL	
		PARTICULATES	NOx	HYDROCARBON	CARBON MONOXIDE	IGNITION QUALITY	MAXIMUM PRESSURE	CCR CETANE	AVERAGE TORQUE	ASSESSMENT	RANK
1	100	100	100	100	100	100	100	100	100	900	1
2	97(E)	95	100	94	100	90	99	99	103	877	4
3	96	92	91	91	97	77	97	93	94	830	18
4	94	98	100	92	95	96	95	83	90	843	16
5	93	96	113	90	91	110	105	70	85	853	13
6	94	94	139	88	86	118	107	61	81	868	10
7	91(E)	90	156	84	70	125	105	59	77	856	11
8	93	88	102	94	97	85	101	92	88	840	17
9	90	90	104	92	89	98	102	75	81	821	19
10	88	87	109	89	86	118	105	64	76	822	19
11	90	85	109	82	94	108	101	72	76	817	21
12	93	105	98	83	94	85	95	113	102	868	9
13	102	108	116	115	90	74	94	95	105	899	2
14	102	93	109	107	93	80	99	100	86	869	8
15	100(E)	100(E)	115	108(E)	95(E)	82	96	93	103	892	2
16	100(E)	90	111	106	97	80	100	98	94	876	5
17	90	95(E)	98	101(E)	97(E)	77	104	83	91	836	15
18	101	102	109	104	93	100	99	100	87	895	6
19	102	100	109	105	75	98	99	79	107	874	6
20	91	98	102	96	97	85	104	90	91	854	12
21	93	99	111	95	92	92	101	78	89	850	14
22	70	75	104	84	92	70	72	75	114	756	22
23	-	-	-	-	-	85	100	90	88	N/A	

Note: (E) = estimated

TABLE 26: OVERALL RATING OF FUELS

Moderate Efficiency Blends: 5% and 10% methanol in #1 diesel have energy efficiencies only somewhat lower (97, 96%) that of #1 diesel fuel.

Intermediate Efficiency Blends: This group contains all fuels with a measured efficiency from 95% to 91% that of #1 diesel fuel. This group is comprised of #1 diesel blended with 15-30% methanol without ignition improver, a #1 diesel blend with 15% methanol which was cetane-improved and two cetane-improved #2 diesel-methanol blends (15, 20% methanol). This intermediate energy efficiency group also contains a #1 diesel 5% water blend, cetane improved by an organic nitrate (compare with the high efficiency fuels containing water and inorganic salts).

Low Efficiency Blends: The lowest efficiency of all samples was given by the "1990 diesel". Others with unsatisfactory efficiency (88-90% that of #1 diesel) include ignition improved blends of #1 diesel containing methanol at the 25 and 30% level and highly oxygenated water (7.5% volume) and methanol (7.5% volume) composition. It is of interest to note that all oxygenated fuels had energy efficiencies substantially better than that exhibited in these tests by the 1990 diesel fuel.

There is clearly a need to test these samples in a standard fuel economy cycle.

Pollution

A judgmental combination of pollution measurements involving particulates, NOx, carbon monoxide and unburned fuel was used to produce the pollution index values of Table 27, p. 28. This is no substitute for a 13-mode steady state test or tests involving engine transients, but is broadly indicative of the fuel-engine pollution performance.

Low Pollution: Pollution performance equal to or better than that of #1 diesel fuel was shown by certain oxygenated blends with #1 diesel fuel. These contained 25% and 30% methanol (no cetane improver), or water at the 5% level (with and without organic cetane improver) and at the 5.5% level (with ammonium nitrate added). Surprisingly low pollution levels were indicated with the blend of #1 diesel with the Dalco reagent itself.

Intermediate Pollution: The blends of #1 diesel (clear, i.e. without cetane improver) with 5,15 and 20% methanol were judged to have produced an intermediate level of pollution. Cetane-improved #2 diesel blends with methanol (15,20% methanol) and cetane-improved 15% methanol in #1 diesel fuel were also in this category. The intermediate pollution group included two organic nitrate, cetane-improved #1 diesel samples containing water: one at the 5% water level, the other containing water, 7.5% volume and methanol, 7.5% volume.

FUEL SAMPLE #	ENERGY EFFICIENCY		POLLUTION		ENGINE PERFORMANCE		OVERALL	
	INDEX	RANK	INDEX	RANK	INDEX	RANK	INDEX	RATE
1	100	5	400	7	400	1	900	1
2	97(E)	8	389	13	391	3	877	5
3	96	9	371	19	363	16	830	18
4	94	10	385	15	364	15	843	15
5	93	12	390	12	370	8	853	13
6	94	10	407	5	367	11	868	9
7	91(E)	16	400	7	366	12	856	11
8	93	12	381	16	366	12	840	16
9	90	18	375	18	356	20	821	20
10	88	21	371	19	363	16	822	19
11	90	18	370	21	357	19	817	21
12	93	12	380	17	395	2	868	9
13	102	1	429	1	368	10	899	2
14	102	1	408	3	365	14	869	8
15	100(E)	5	418	2	374	6	892	4
16	100(E)	5	404	6	372	7	876	6
17	90	18	391	11	355	21	836	17
18	101	4	408	3	386	4	895	3
19	102	1	389	13	383	5	874	7
20	91	16	393	10	370	8	854	12
21	93	12	397	9	360	18	850	14
22	70	22	355	22	331	22	756	22
23	-		-		363	N/A	N/A	

Note: (E) = estimated

TABLE 27: FUEL RATING INDEX

High Pollution Fuels: This group comprised blends of #1 diesel with 10% methanol (no ignition improver), and ignition improved methanol at the 25% and 30% level. The 1990 diesel fuel was distinctly inferior to all oxygenated blends with respect to pollution output.

The conclusion with respect to exhaust emissions is that very complex and competing combinations are evident since the ranking of the oxygenated fuels follows no easily identified pattern. Furthermore, the relative levels of the various emissions vary as much with changes in the engine settings as with changes in the fuel composition.

Tests of the low and intermediate pollution prospects under transient engine (setting) conditions would provide useful additional information on the prospects of these fuels and might alter their rankings somewhat.

Engine Performance

The composite of engine test data used to produce an overall "engine performance index" included two measurements related to fuel ignition quality. The first involved measurements of ignition delay at a variety of engine speeds and load conditions in a warmed-up engine. Also included in the "engine performance index" is the ignition delay measured by the CCR method where comparisons of the measured cetane values obtained in a cetane standardized engine using #1 diesel fuel and the blends, provided information related to the cold starting capability of the fuel and other quality parameters associated with cetane quality value in conventional diesel fuels.

It is of interest to note that, notwithstanding large variations in oxygen content and CCR cetane values within the group of oxygenated fuels tested, there was no severe performance degradation and performance of all the blends was superior to that of the 1990 diesel fuel under the given conditions. Testing of the oxygenated fuels with cycles which include cold engine operation and transients would no doubt have given a more varied engine performance response to fuel changes.

High Engine Performance: The test engine was designed for diesel fuels: it is therefore not unexpected that the highest performance was shown by #1 and #2 diesel fuels.

Three oxygenated fuels were included in this group: #1 diesel fuel containing 5% methanol; a cetane improved #1 diesel fuel with 5% water and a clear (no cetane improver) #2 diesel fuel containing 15% methanol.

Intermediate Engine Performance: The following groups of fuels gave adequate engine performance: #1 diesel with 2.5% Dalco; three #1 diesel-water blends (two containing 5% water and Dalco only, one with and one without an organic cetane improver, another with 5.5% water and ammonium nitrate cetane improver); two cetane-improved blends with high level of methanol (one of #1 diesel with 15% methanol, another with 15%

methanol in #2 diesel fuel); five methanol blends in #1 diesel (at the 10%, 15%, 20%, 25% and 30% methanol by volume level).

Low Engine Performance: In addition to the 1990 fuel this group contains high level oxygenated blends: one containing 25% methanol (cetane improved), another 30% methanol in #1 diesel fuel (both with and without cetane improver), yet another containing 20% methanol in cetane improved #2 diesel fuel. The high level water-methanol composition (7.5% water, 7.5% methanol in cetane improved #1 diesel fuel) was also in this category.

It appears that engine performance is satisfactory to excellent with a number of fuels in which water or methanol is used at the 5% level. In general, satisfactory performance was also achieved with #1 diesel fuel formulated with methanol over a wide range 5-30% without cetane improvers. High methanol content blends with cetane improved #1 diesel fuel show inadequate engine performance according to the present test methods.

Overall Fuel/Engine Performance Evaluation

Four categories are used to provide an overall, judgemental assignment of fuels on the basis of efficiency, exhaust emissions, engine performance under the favourable steady state test conditions and cetane values.

Excellent Overall Performance: In addition to diesel #1 and #2 and Dalco-#1 diesel fuel, three Dalco-stabilized emulsions stand out as having an excellent overall performance rating under the given test conditions:

- 5.5% water in #1 diesel fuel with ammonium nitrate added
- 5% water in #1 diesel with iso-octyl nitrate and barium acetate added
- 5% methanol in #1 diesel fuel

These fuels had excellent CCR rating and fuel economy.

Good Overall Performance: This group includes five fuels with a high to intermediate level of methanol and two using 5% water (all with Dalco emulsifier added) but high measured-in-engine "ignition quality":

- 20, 25, 30% methanol in clear (no cetane improver) #1 diesel fuel (low cetane values)
- 15% methanol in #2 diesel (cetane improved to two levels)
- 5% water (with and without the organic nitrate cetane improver) (high cetane values)

Inadequate Performance: The five oxygenated fuels in this category all contained intermediate levels of oxygenates and the Dalco emulsifier in diesel fuel as follows:

- 10% methanol in #1 diesel (clear)

- 15% methanol in #1 diesel (clear and cetane improved)
- 20% methanol in #2 diesel (cetane improved)
- 7.5% methanol and 7.5% water (cetane improved)

Very Poor Performance: #1 diesel-Dalco blends formulated with 25% and 30% methanol provide very poor overall performance: only the 1990 diesel exhibited a lower overall performance. The fuels in question although fortified with organic nitrate ignition improvers had exceptionally low CCR cetane values.

The fuels with excellent performance all had high CCR cetane values, the fuels with the poorest overall performance all had low CCR cetane values but cetane values alone did not determine overall performance as evidenced by the spread of CCR cetane values among the much larger "good" and "inadequate" performance rated groups. Some of the fuels with low CCR cetane showed up better in the ignition delay measurements in the tests with the engine dynamometer.

Substantial further data analysis and tests will be required to draw more concise correlations between fuel composition and each aspect of the fuel/engine performance. This analysis should be undertaken if further testing under transient engine conditions is to be undertaken.

7.0 ECONOMIC CONSIDERATIONS

7.1 DALCO AVAILABILITY

The Dalco emulsifier is entirely carbon hydrogen oxygen based. The raw materials for the manufacture of the compounds comprising the emulsifier are widely available at low cost. The manufacturing process does not involve extremes of temperatures or pressures and thus is not problematic to construct and operate.

Albright & Wilson Limited currently holds a non-exclusive world-wide licence from Apace Research Limited, the originators of the technology. Albright & Wilson have produced a number of tonnes of Dalco for engine demonstration trials and test programs and will expand or install production capacity as the markets develop.

7.2 THE COSTS OF SELECTED FORMULATIONS AT CURRENT PRICES

The economics of using emulsified diesel methanol fuel blends is a function of the following direct cost factors:

a) Diesel Fuel Cost;
b) Methanol Fuel Cost;
c) % Methanol in Blended Fuel;
d) Emulsifier Cost;
e) % Emulsifier Required;
f) Fuel Blending Cost;
g) Blended Fuel Efficiency relative to Diesel Fuel.

The commercialization of diesel methanol fuel blends is heavily dependent on the ability of the blended fuel to offer a fuel cost efficiency equivalent to that of neat diesel fuel. This will be modified somewhat by environmental considerations, engine durability and the tax status of blended fuels versus diesel fuels.

The equivalent cost requirement may be expressed as:

$$\frac{\text{Cost of Blend}}{\text{Blend Efficiency}} \leqslant \text{Diesel Costs}$$

which may be further developed to the following expressions:

$$\frac{(1 - M\% - ZM\%)\ \text{¢}_D + M\%\ C_M + Z\ M\%\ \text{¢}_{DA} + \text{¢}_B}{BE} \leqslant C_D$$

Where $M\%$ = Percentage of Methanol in blend, decimal
¢_M = Cost of Methanol, cents per litre
Z = Percentage of Dalco as percentage of Methanol, decimal
¢^{DA} = Cost of Dalco, cents per litre
¢_D = Cost of Diesel, cents per litre
BE = Blend efficiency relative to neat Diesel, decimal
¢_B = Blending Cost, cents per litre

Using this expression, the various breakeven scenarios and cost sensitives may be evaluated.

7.2.1 Diesel Fuel Prices Canadian

1) Source: Oil Buyers Guide Sept 9/85.

A) Canadian Terminal Prices - Rack Contract ¢ Cnd/L

	Halifax,	Montreal,	Toronto,	Edmonton,	Vancouver
Diesel	30.2	28	27.15	28.9	29.1
	31.2	29	27.35	29.9	31.1

B) Esso Industrial Accounts ¢ Cdn/L

	St. John,	Montreal,	Toronto,	Edmonton,	Vancouver
Diesel	33.4	30	29.5	30.2	31.0

Prices in A&B exclude Federal Tax of 2.9¢/L and Provincial Tax.

2) Source: Energy Pricing News, Aug. 1985

A) Contract prices including Federal Taxes of 2.9¢/L.

	Halifax,	Montreal,	Toronto,	Edmonton,	Vancouver
Diesel	34.5	30.8	29.7	26.4	27.8
	35.6	32.9	32.4	31.1	33.9

The prices quoted in 1,B, above are in agreement with others quoted and would represent the types of accounts to which blended fuels would be marketed.

7.2.2 Methanol - Fuel Additive - Canadian Prices

1) Fuel additive methanol is quoted as 15¢/L FOB Edmonton. Using jumbo tank cars, the following prices are estimated for anyhdrous methanol.

Halifax,	Montreal,	Toronto,	Edmonton,	Vancouver
22¢/L	19¢/L	19¢/L	15¢/L	17¢/L

2) Fuel grade methanol is presently priced at 39¢ US/US, West Coast and U.S.A. This is equivalent to 14.3¢ Cdn/L.

7.2.3 % Methanol in Blended Fuel

The test work has shown that it is possible to run up to approximately 20% Methanol in an unmodified engine and remain within manufacturer's specification on rates of pressure rise and peak pressure.

A 15% Methanol substitution results in the maximum increase in thermodynamic efficiency. As the blend efficiency affects the costing, the 15% substitution is the most favourable.

7.2.4 Percentage of Dalco in the Blended Fuel

The stability of emulsified fuel is dependent on the percentage of Dalco emulsifier utilized in the blend.

Initial test work has been performed using 0.23% V Dalco per % V Methanol. It has been found that stable emulsions can be made using 0.15% V Dalco per

% V Methanol. Lower concentrations of Dalco may be possible in the future.

7.2.5 Fuel Blending Costs

Blended fuel production requires the three components, Diesel, Methanol and Dalco to be accurately metered and emulsified using high shear mixing.

A blending unit with a capacity of 200 litres/minute will cost an estimated $112,000. Maintenance, depreciation and services for this unit will add an additional cost of 0.4¢/Litre of blended fuel.

7.2.6 Breakeven Scenarios

Using the foregoing costs, various breakeven scenarios may be calculated.

The most favourable costing relationship is low methanol cost, high diesel cost and high blend efficiency.

Methanol costs of 13.5¢/L for 95% hydrated methanol are realistic for large volume movements. The highest diesel fuel pricing which prevails in areas of low methanol pricing is 31¢/L in the Vancouver area. The lowest quantity emulsifier presently possible is 0.15% V Dalco per % V Methanol, while 15% Methanol substitution offers the highest gains in horsepower output of .96 of neat Diesel.

Using these factors, the breakeven price for the surfactant is calculated as 74.8¢/Litre. This is below the estimated production cost. Increases in the diesel fuel price to the 34¢/Litre range combined with further minor reductions in Dalco requirements will make the system competitive.

The relationship between neat diesel fuel and methanol prices for breakeven is shown in Figure 40.

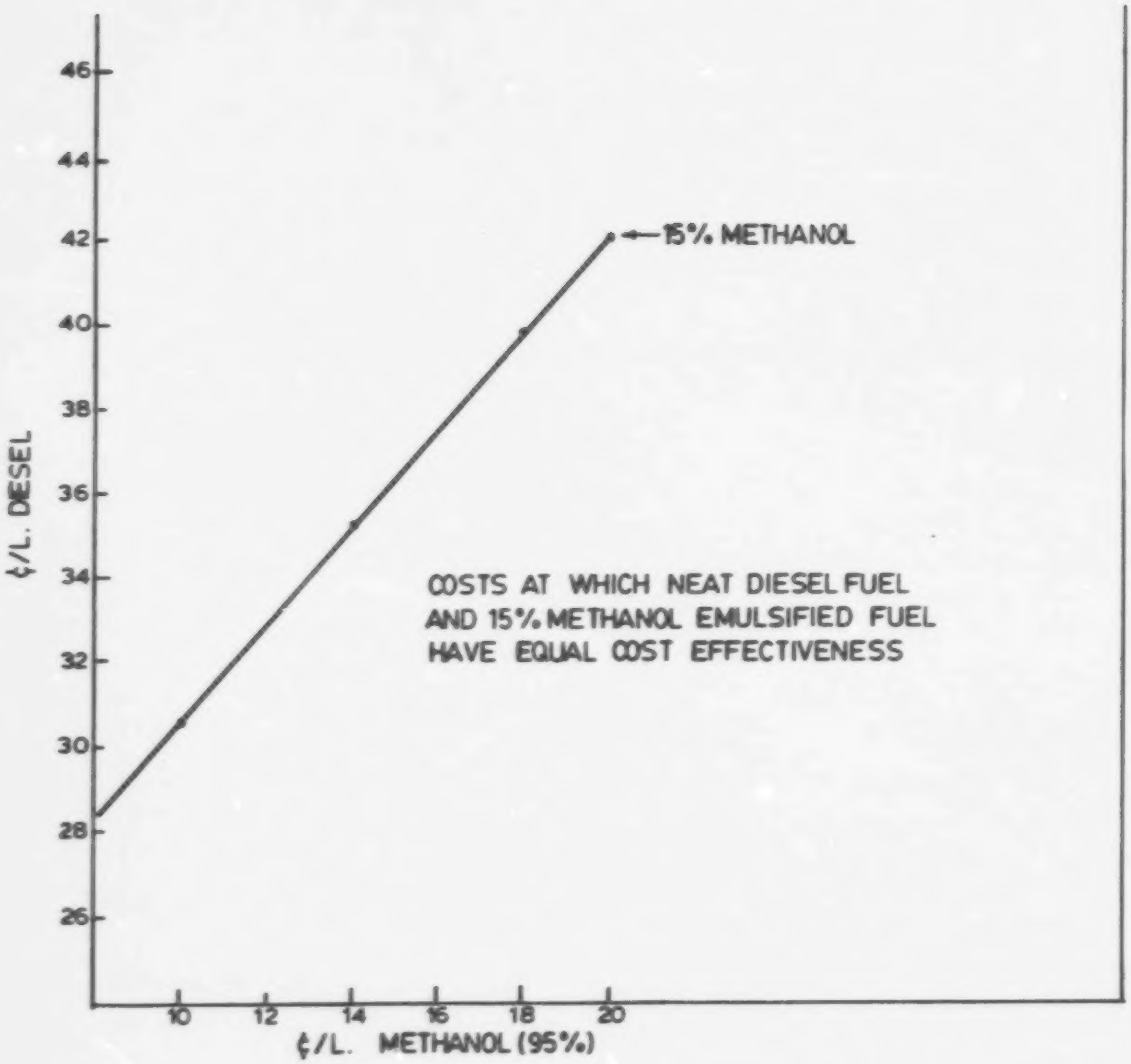

FIGURE 40: EQUIVALENT COST RATIOS FOR DIESEL/METHANOL EMULSIONS

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

It was concluded from the work that:

- Certain useful methanol or water additions to diesel fuel can be made using the Dalco emulsifier. The aqueous emulsions have demonstrated that inorganic salts may be incorporated into formulations which may provide a low cost means to improve blend cetane values and/or reduce particulate emissions. Future work should concentrate on low level methanol or water additions to diesel fuel, reduction in the quantity of emulsifier needed (to improve blend economics) and on testing selected compositions within EPA and industry approved testing regimes.

- The current work did not aim to optimize operations with oxygenated fuel blends. Optimization could change the rankings assigned; inclusions of fuel cost criteria in the evaluation process would no doubt also alter the ranking.

- Even without engine optimization a large number of methanol-diesel and water-diesel emulsions can out perform 1990 diesel in overall engine performance. Low level oxygenated blends may therefore provide a starting point for the eventual expansion of the diesel fuel pool to include blends containing water and methanol with up to 15% volume substitution.

- It is significant that with one minor exception the four cylinder test engine started (admittedly at test cell temperatures of 15 to 20°C) and operated in a highly satisfactory manner on the prepared test fuels. It was also concluded that the stability of the fuels, while not yet perfected, was promising compared to other emulsifying systems.

8.2 RECOMMENDATIONS

It is recommended that:

- Future work shall concentrate on blend optimization now that the principle is established;
- To help in this optimization substantial further data analysis is required;
- The follow-up test program must include transient testing;
- The follow-up test program should include testing of proposed catalyst trap systems to meet 1991 pollution levels to establish the effect of the formulations.

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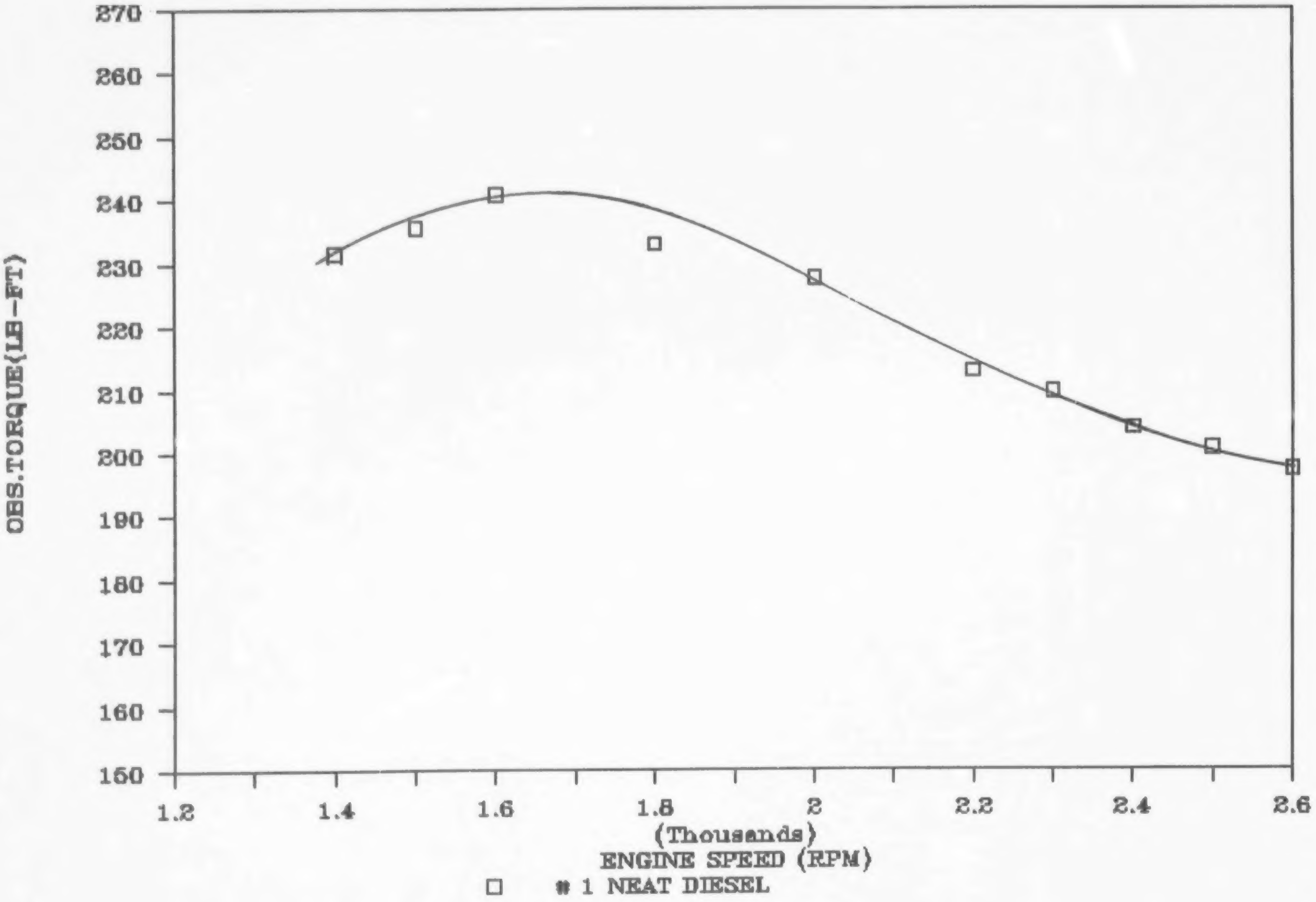
APPENDIX A
COMBUSTION DATA

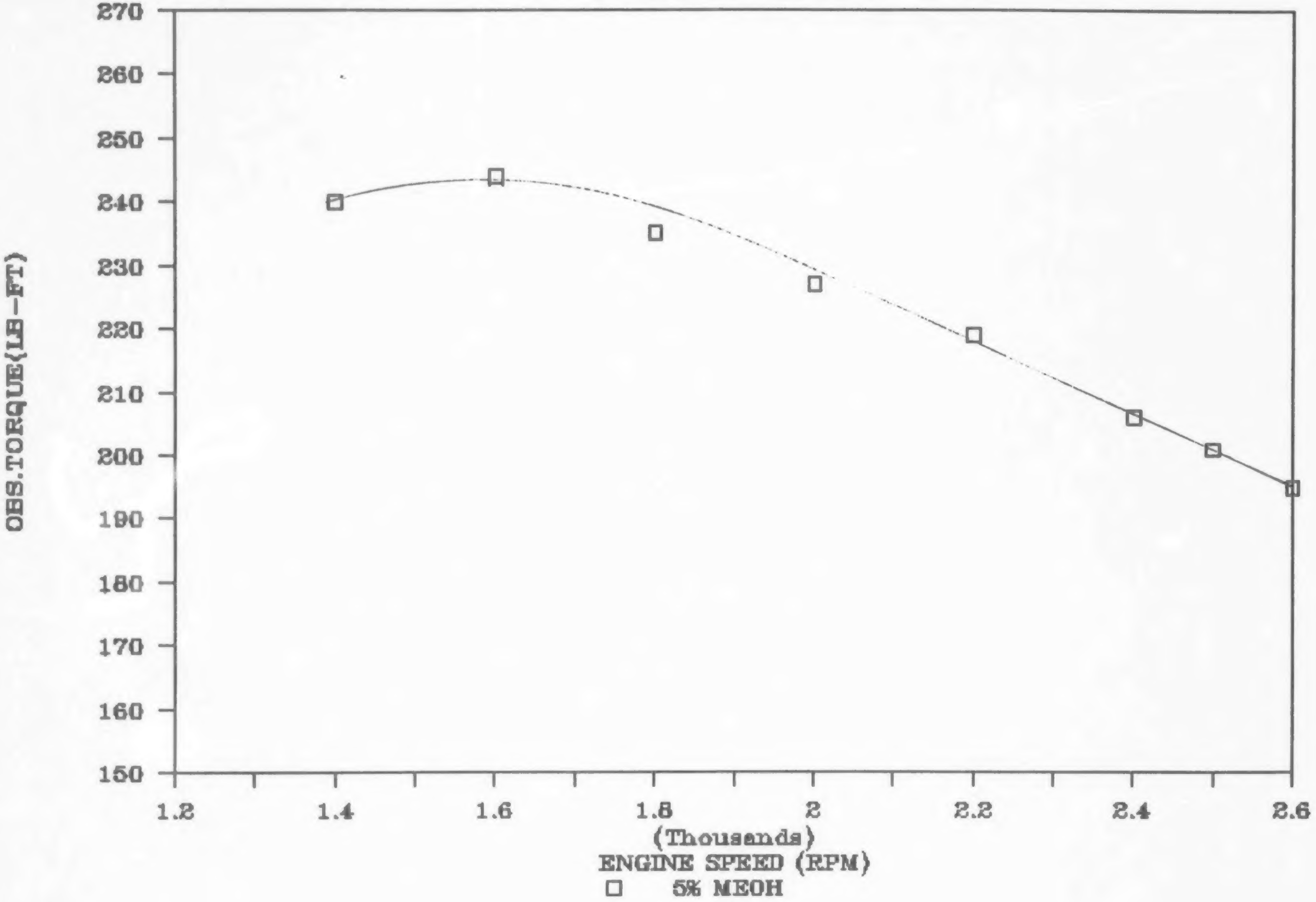
TORQUE CURVE

1 DIESEL



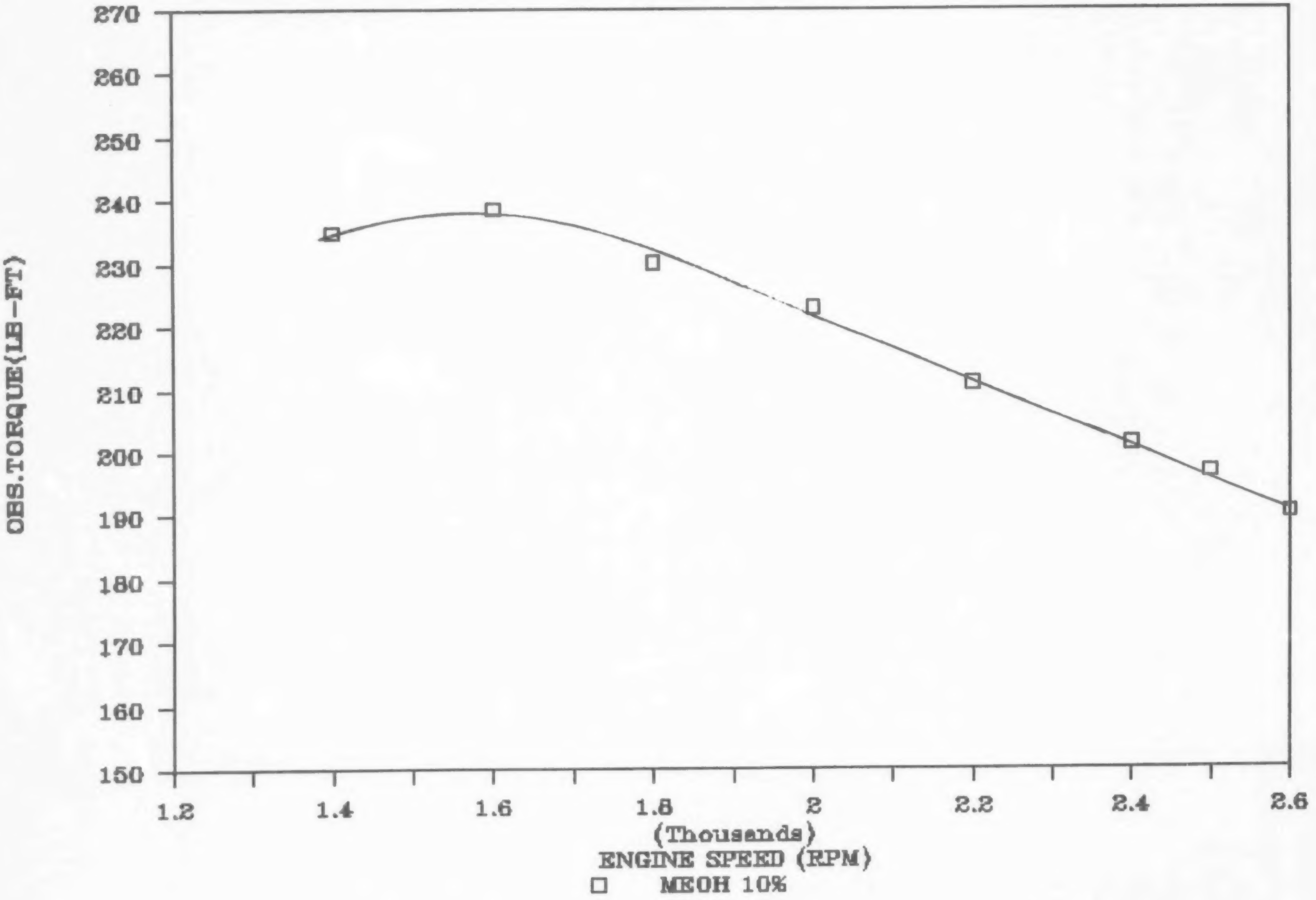
TORQUE CURVE

1 DIESEL + 5% MEOH



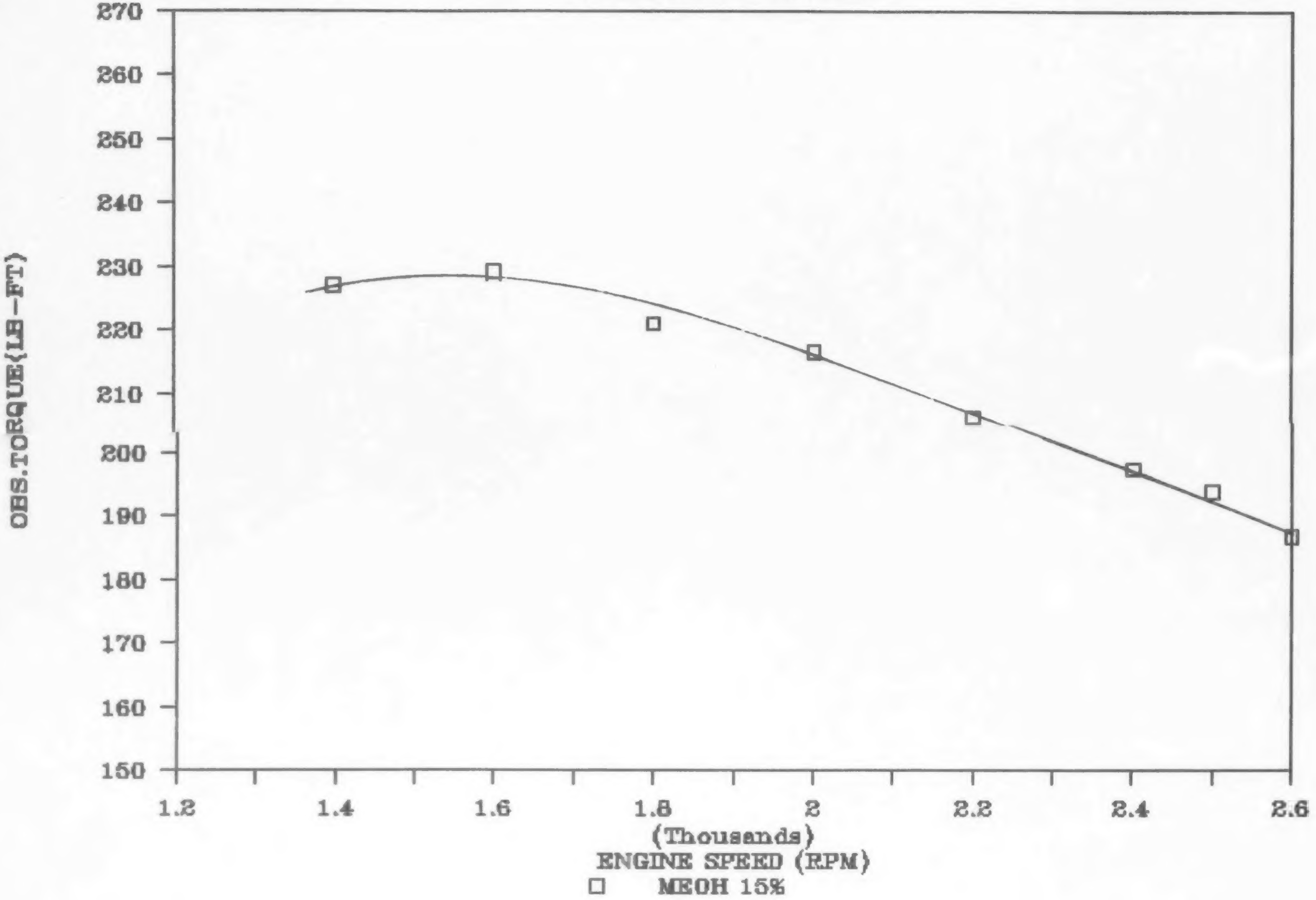
TORQUE CURVE

#1 DIESEL + 10% MEOH



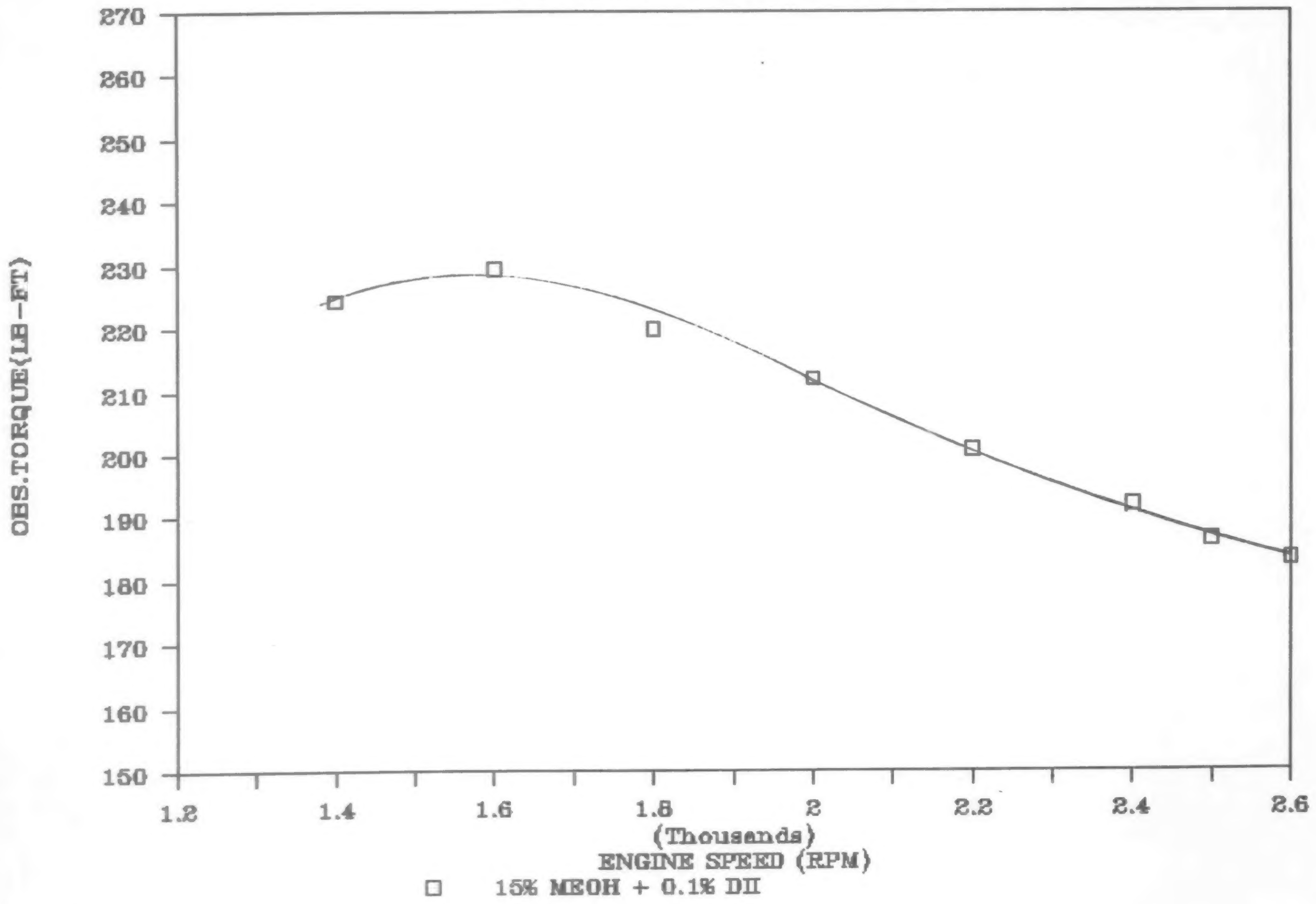
TORQUE CURVE

#1 DIESEL + 15% MEOH



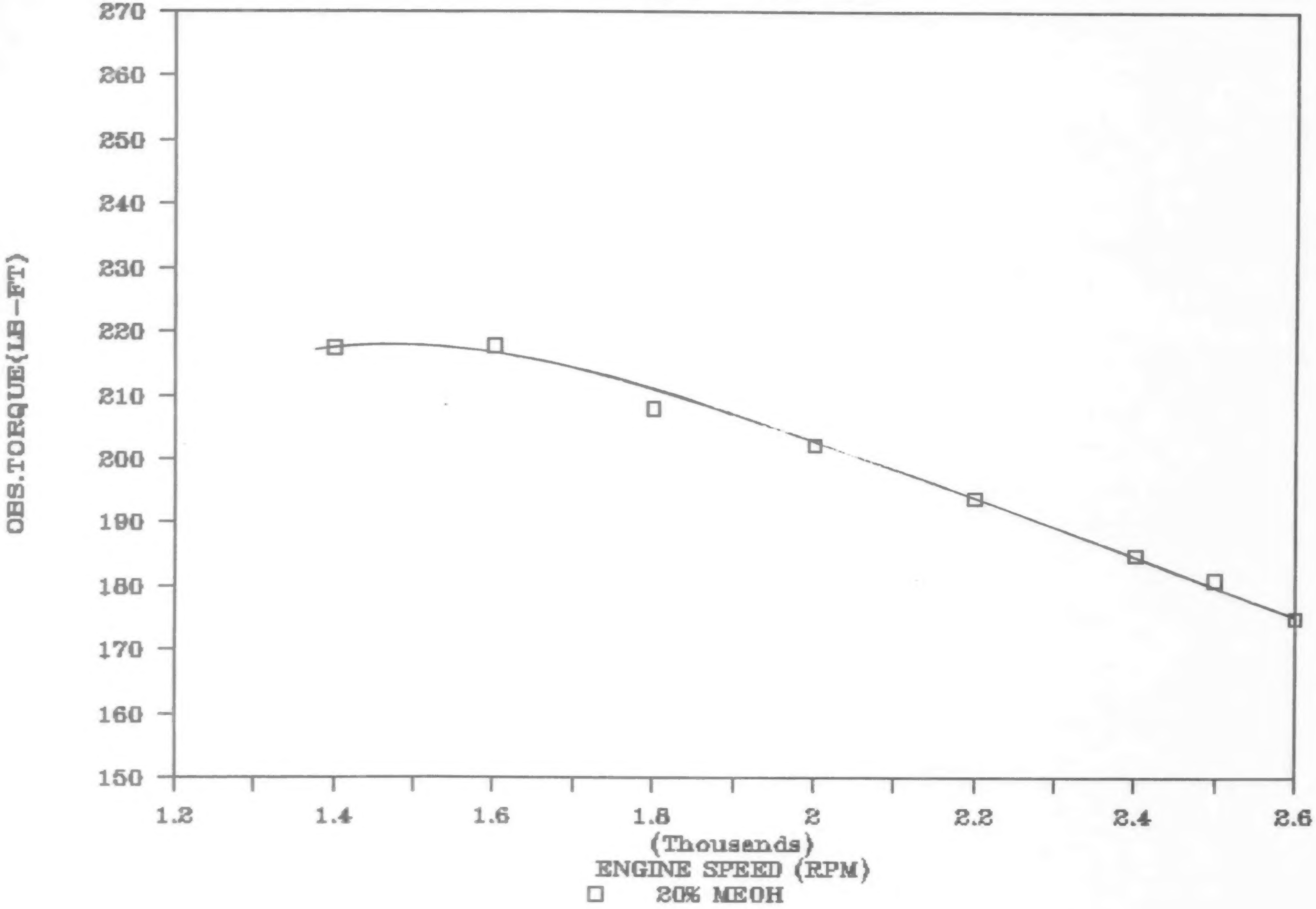
TORQUE CURVE

#1 DIESEL + 15% MEOH + 0.1% DII



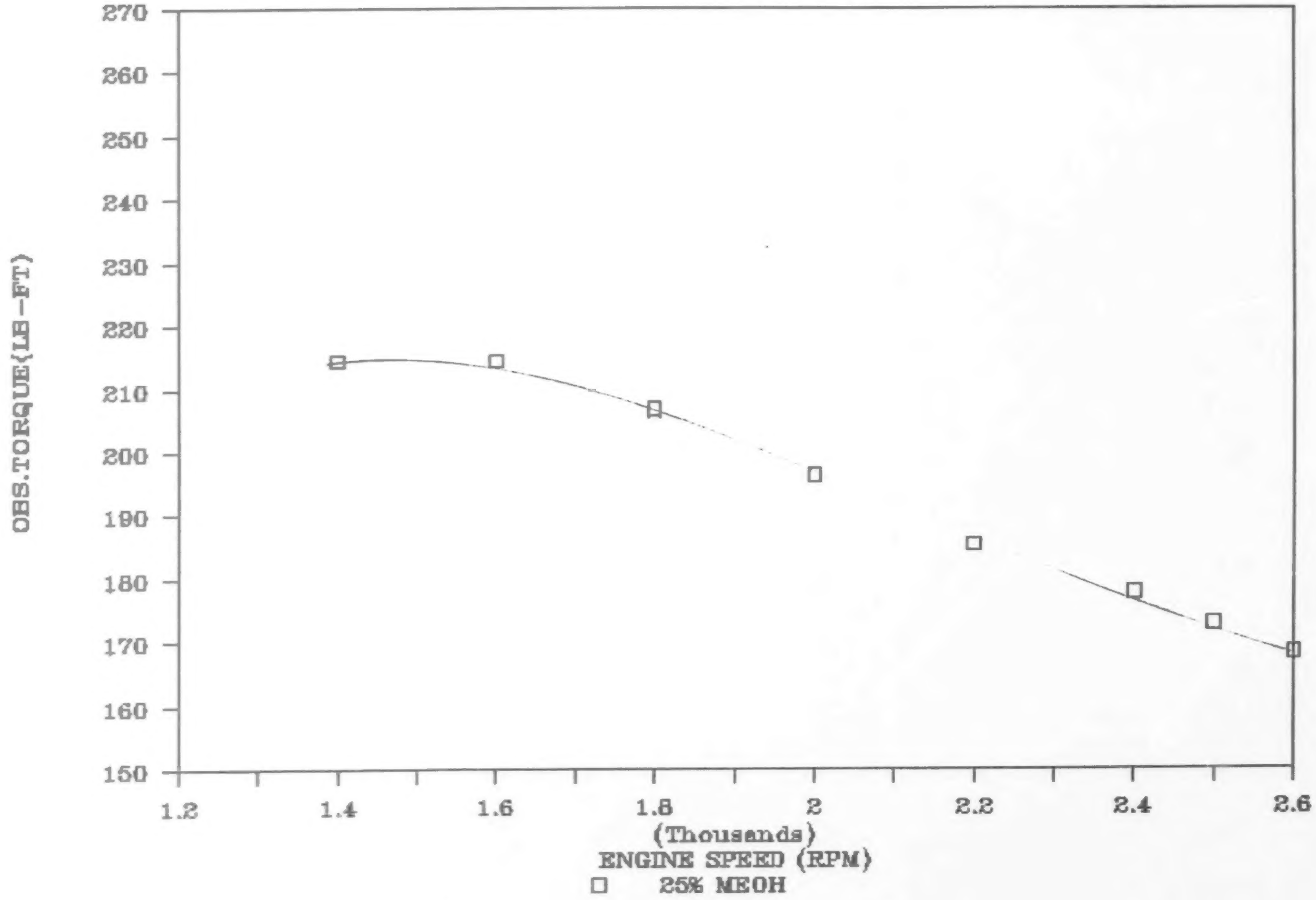
TORQUE CURVE

#1 DIESEL + 20% MEOH



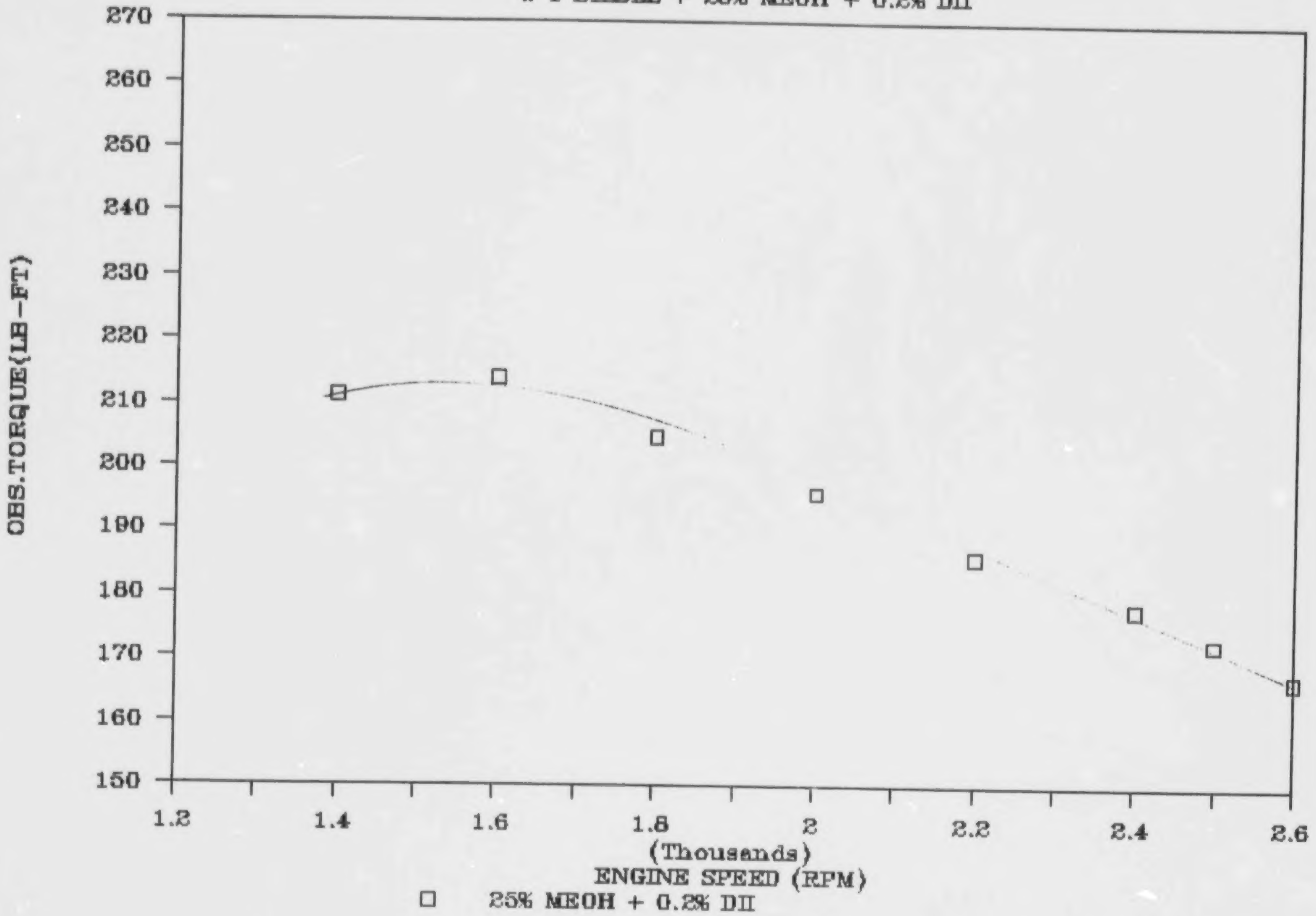
TORQUE CURVE

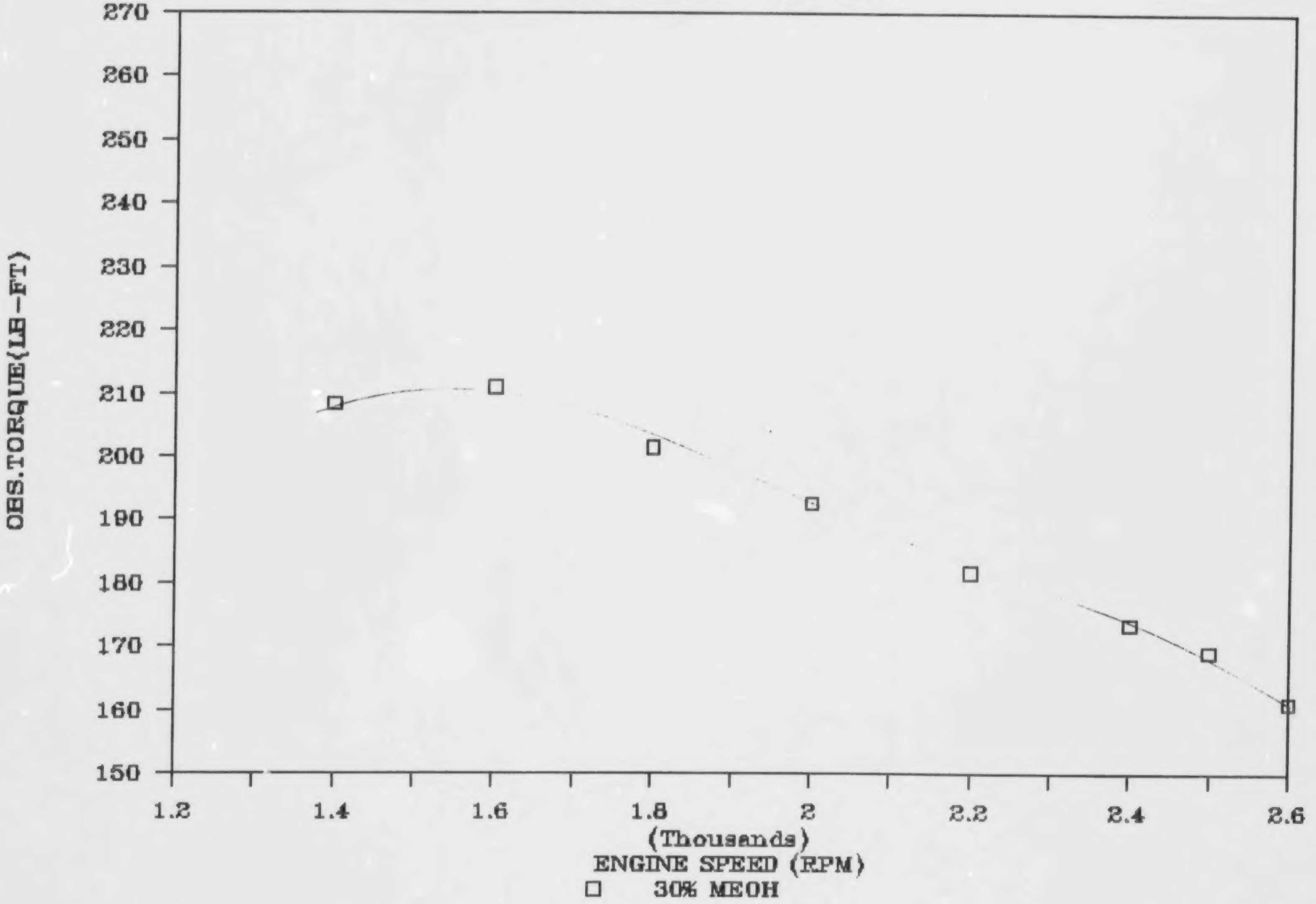
#1 DIESEL + 25% MEOH



TORQUE CURVE

1 DIESEL + 25% MEOH + 0.2% DII



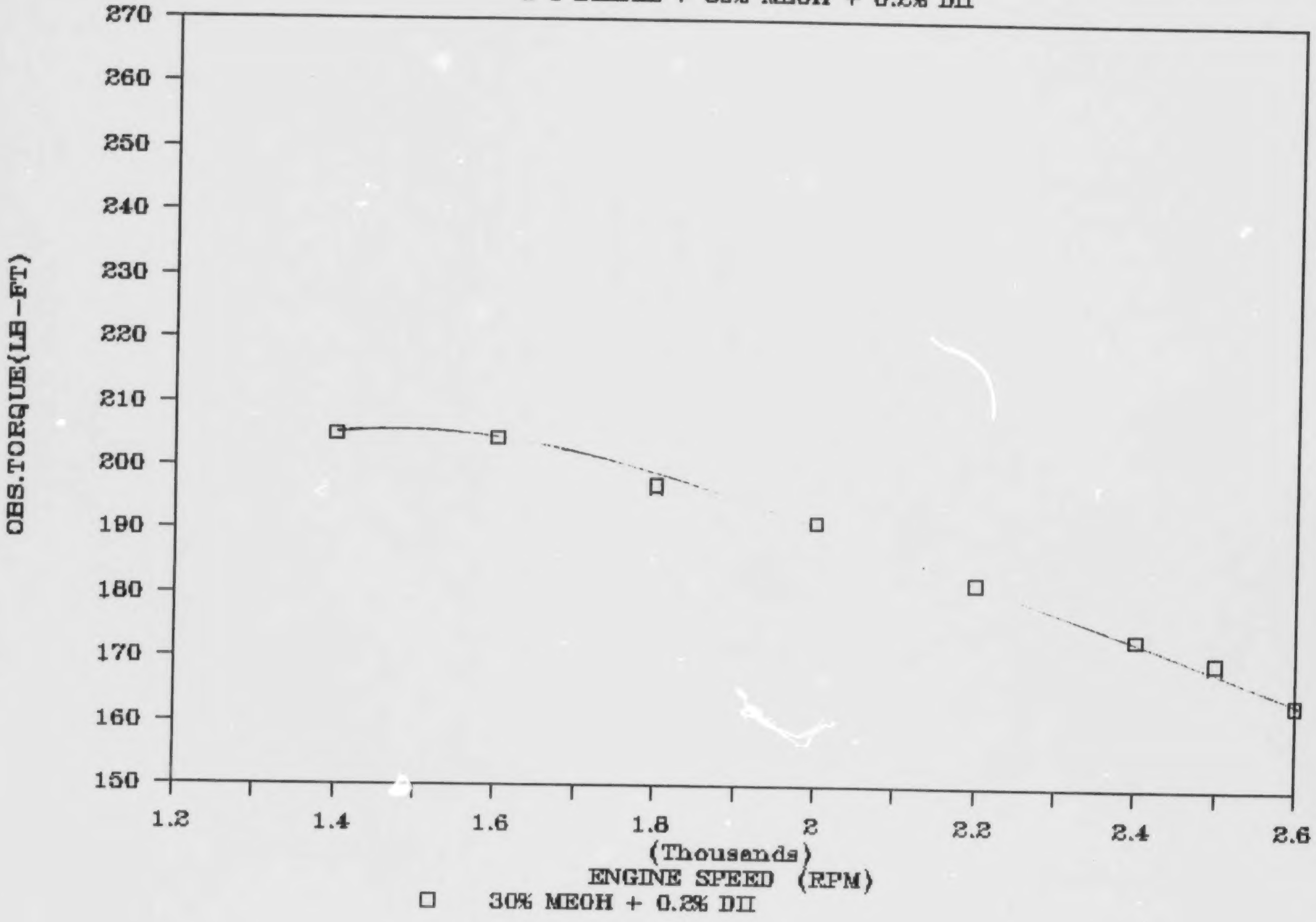


TORQUE CURVE

1 DIESEL + 30% MEOH

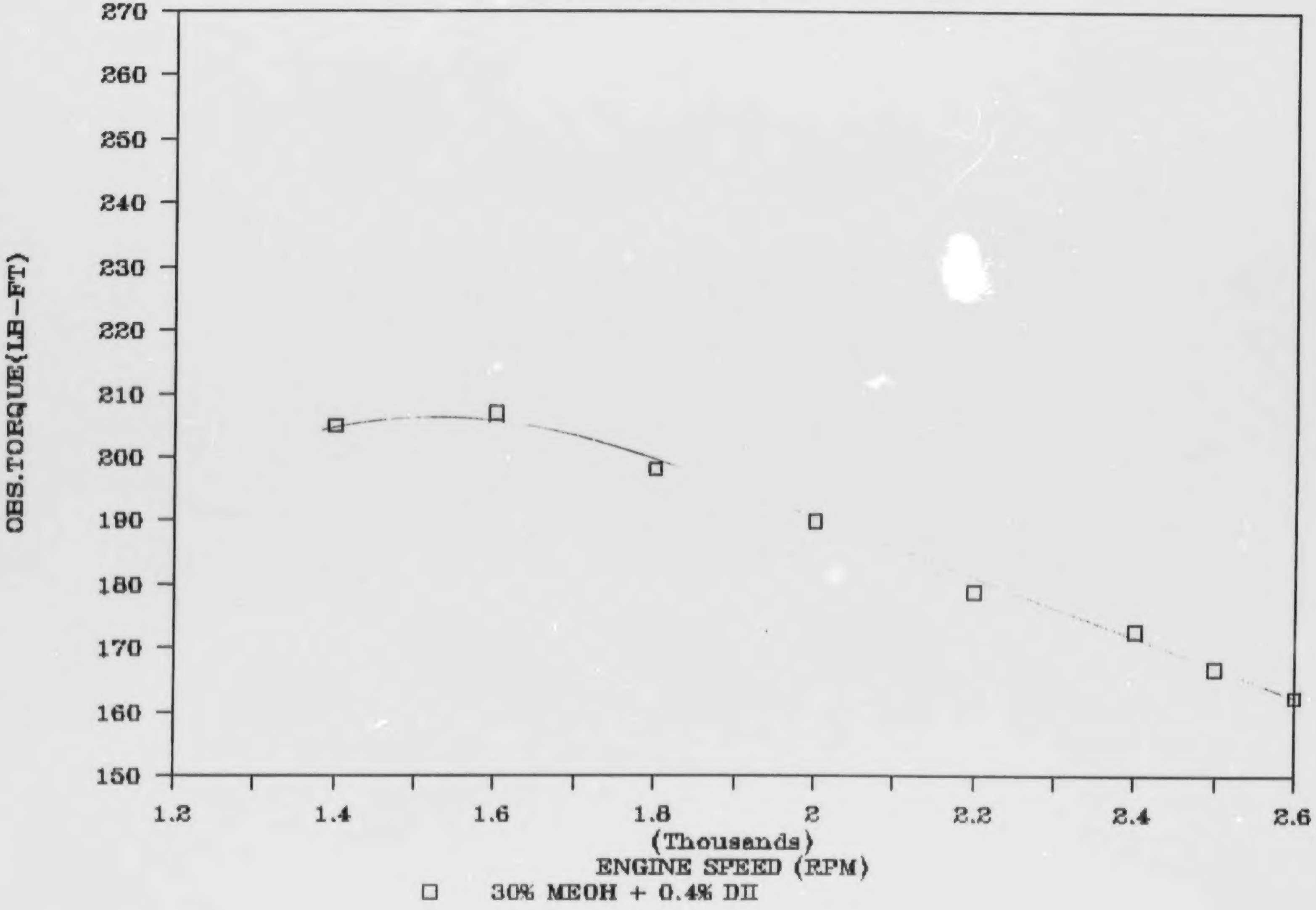
TORQUE CURVE

1 DIESEL + 30% MEOH + 0.2% DII



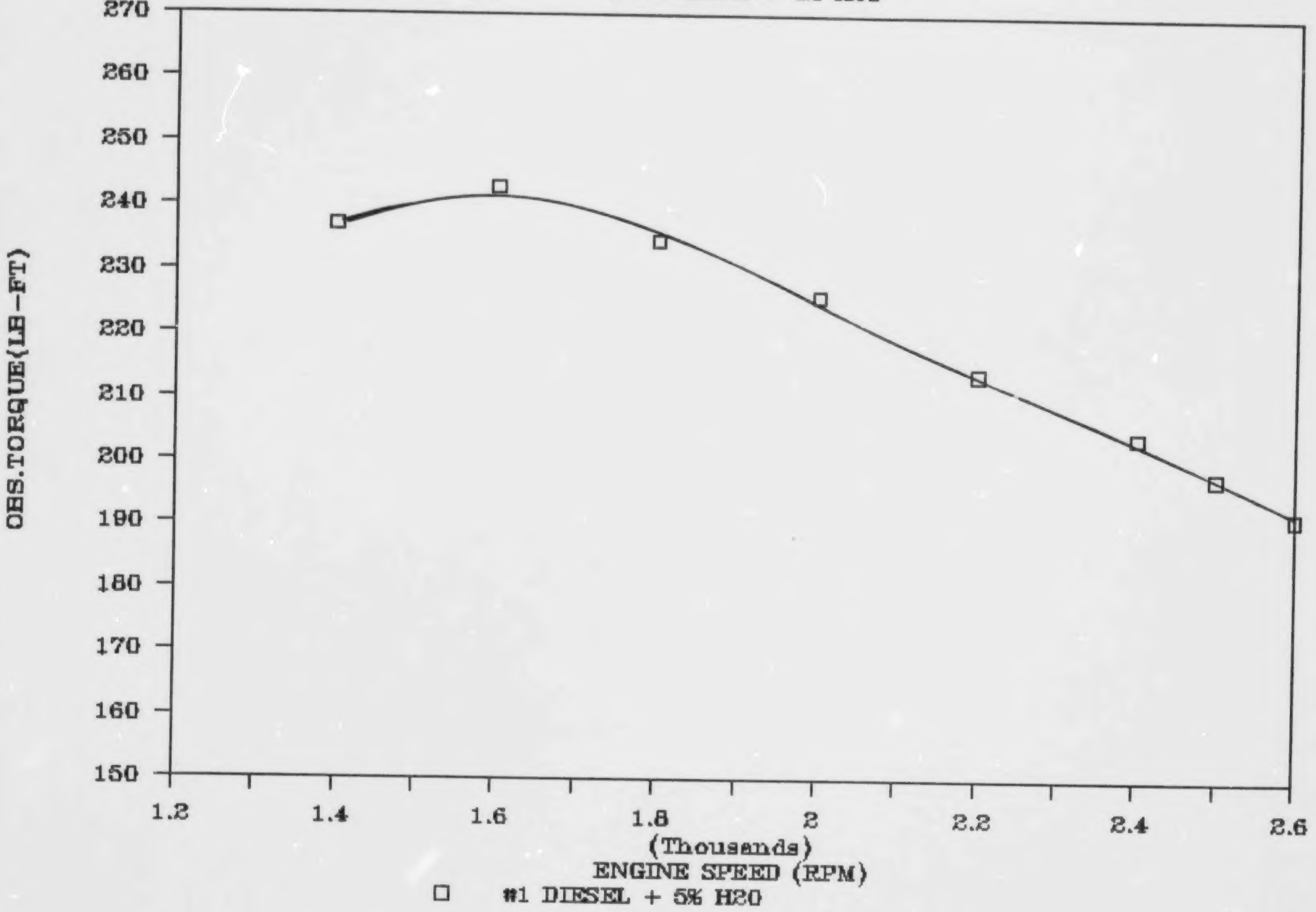
TORQUE CURVE

#1 DIESEL + 30% MEOH + 0.4% DII



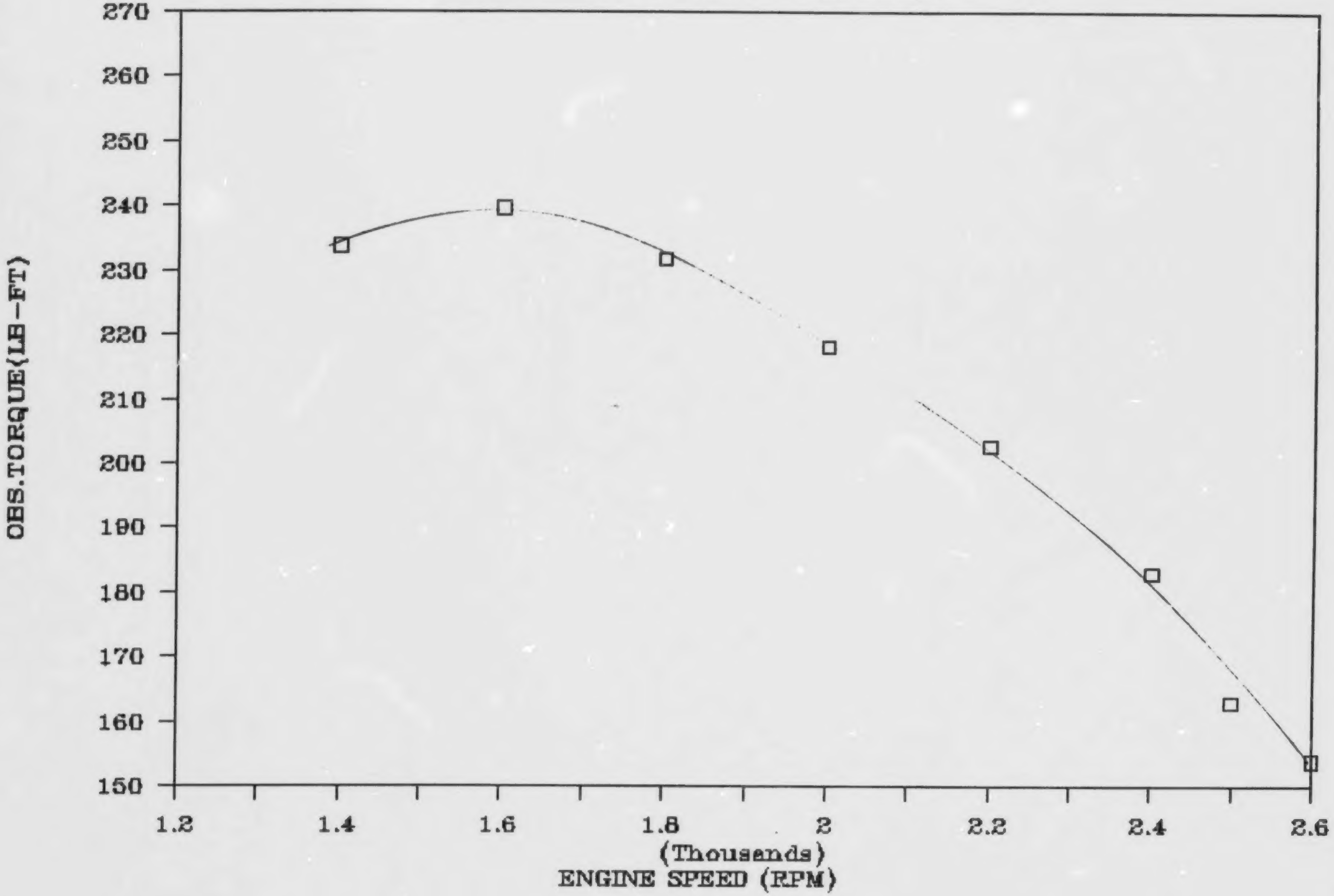
TORQUE CURVE

1 DIESEL + 5% H20



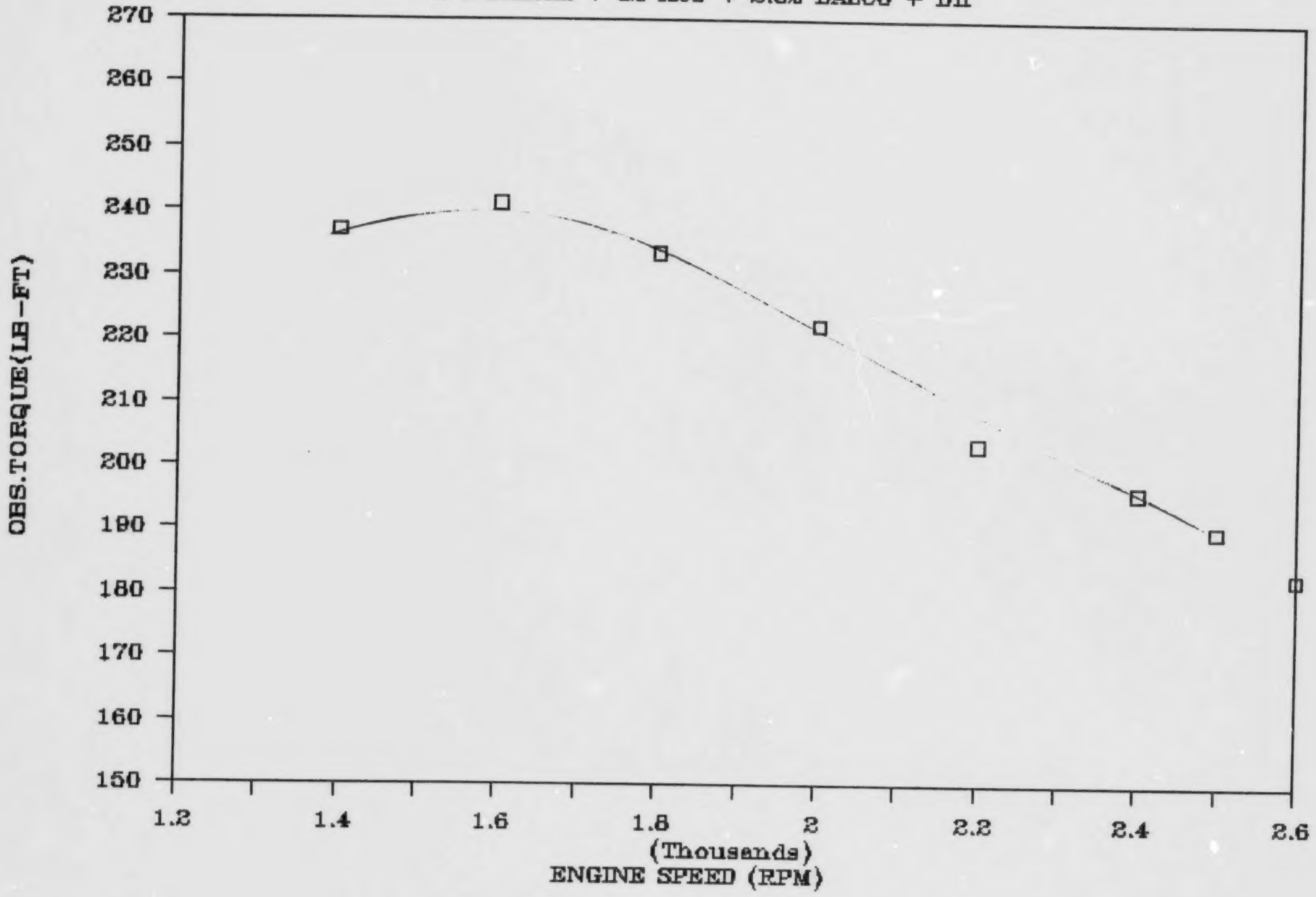
TORQUE CURVE

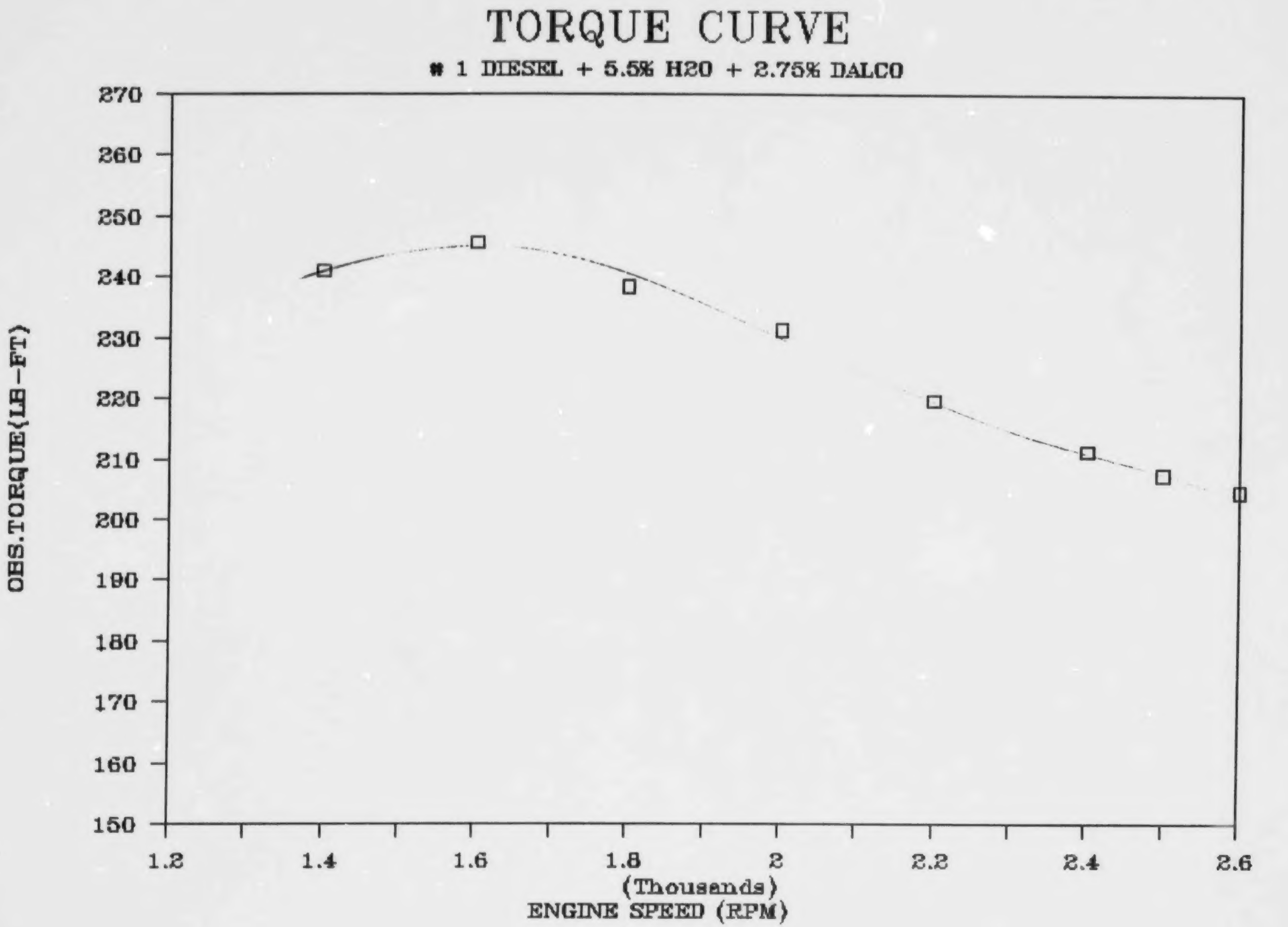
1 DIESEL + 5% H20 + 2.5% DALCO



TORQUE CURVE

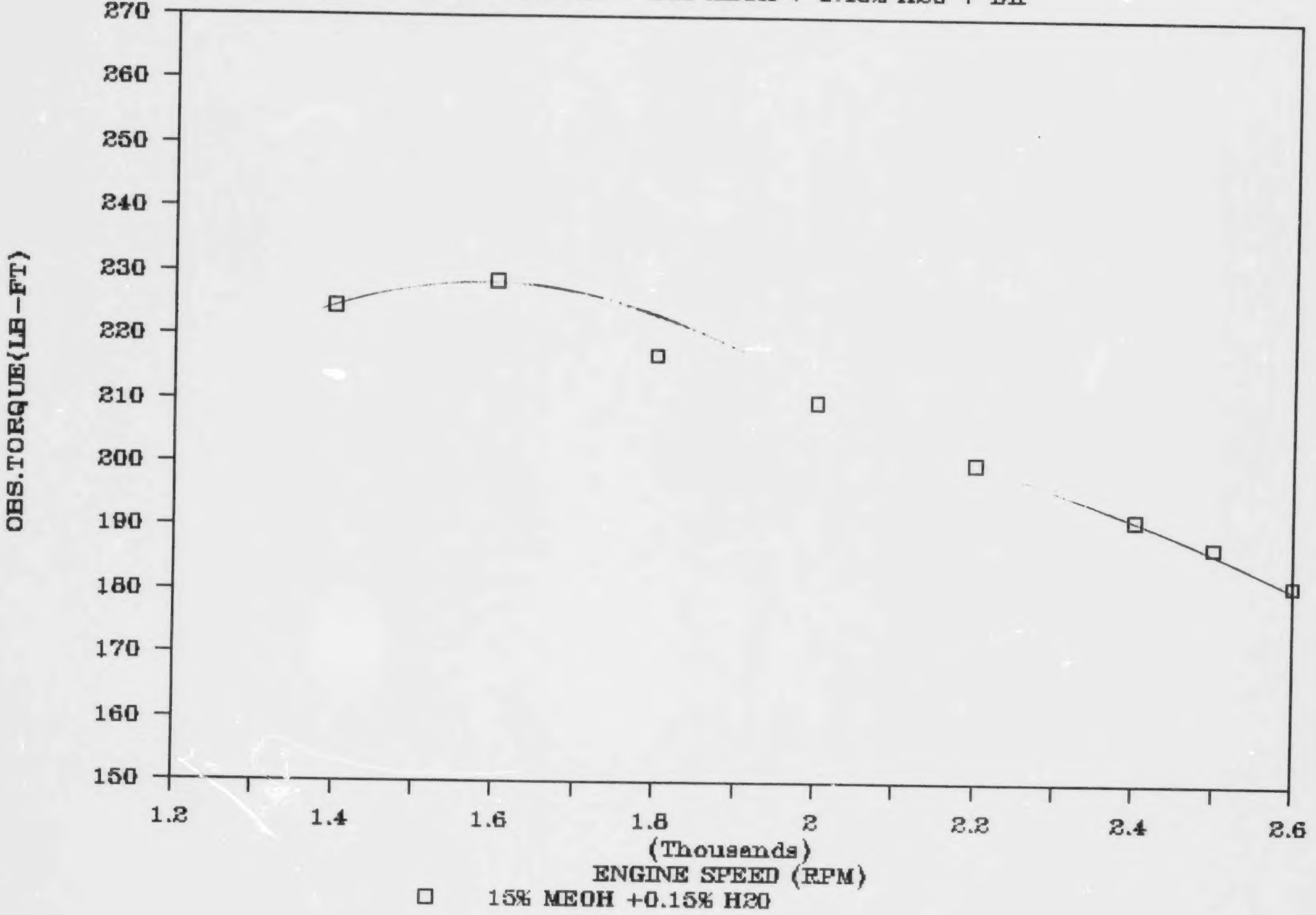
1 DIESEL + 5% H20 + 2.5% DALCO + DII




TORQUE CURVE
# 1 DIESEL + 5.5% H20 + 2.75% DALCO
OBS.TORQUE(LB-FT)
270
260
250
240
230
220
210
200
190
180
170
160
150
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

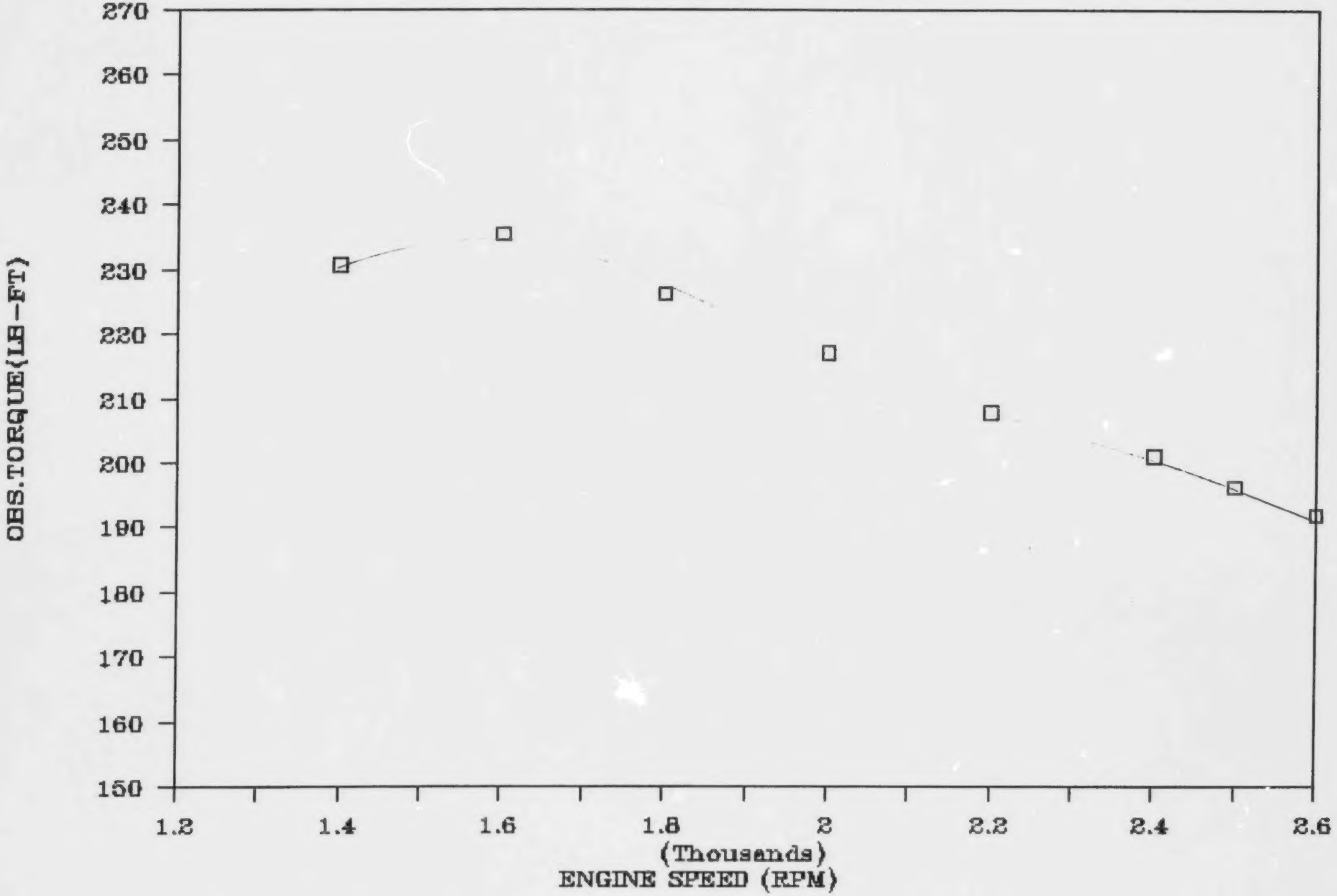
TORQUE CURVE

1 DIESEL + 15% MEOH + 0.15% H20 + DII



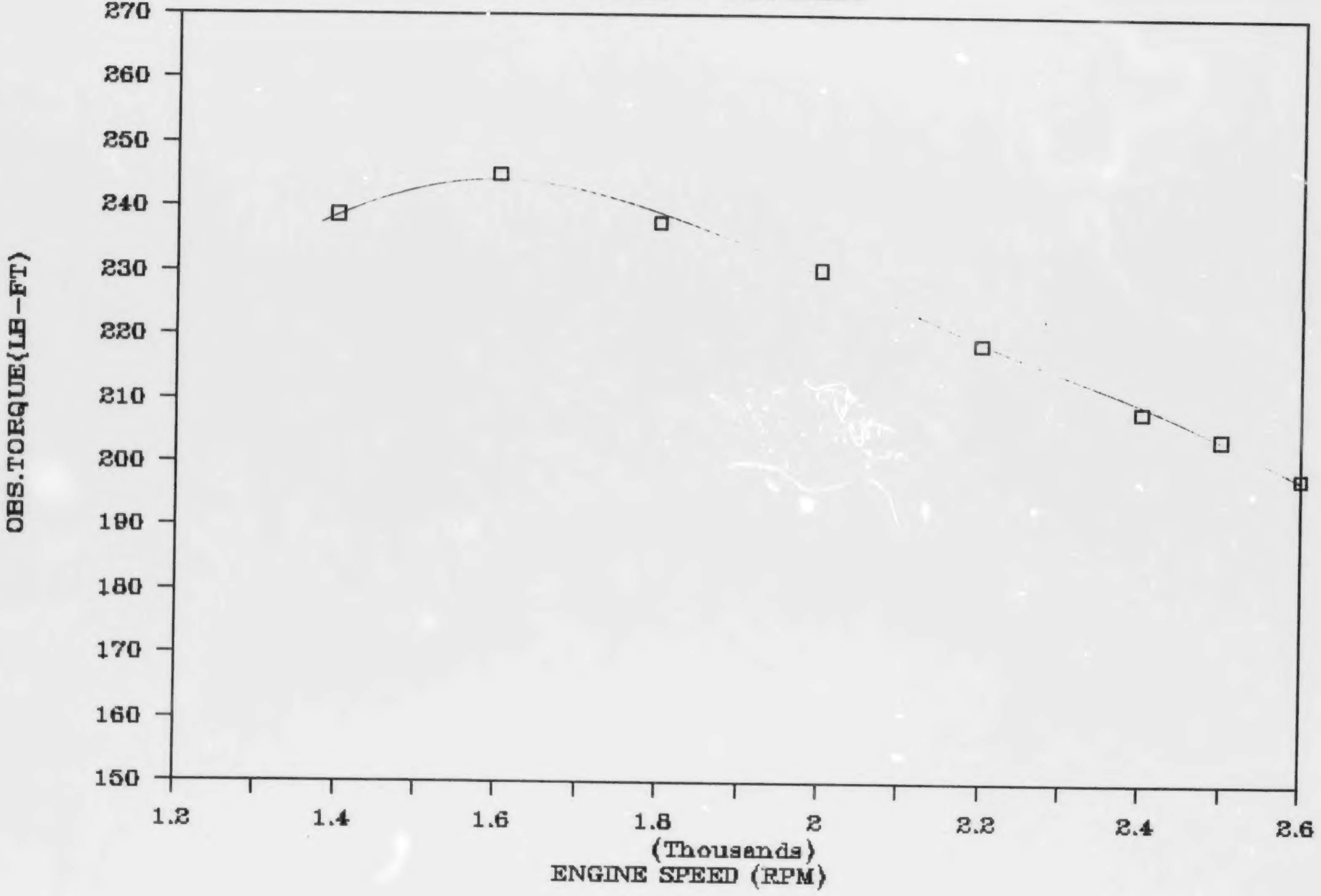
TORQUE CURVE

1 + 7.5%MEOH + 7.5%H2O +0.3%DALCO+DII



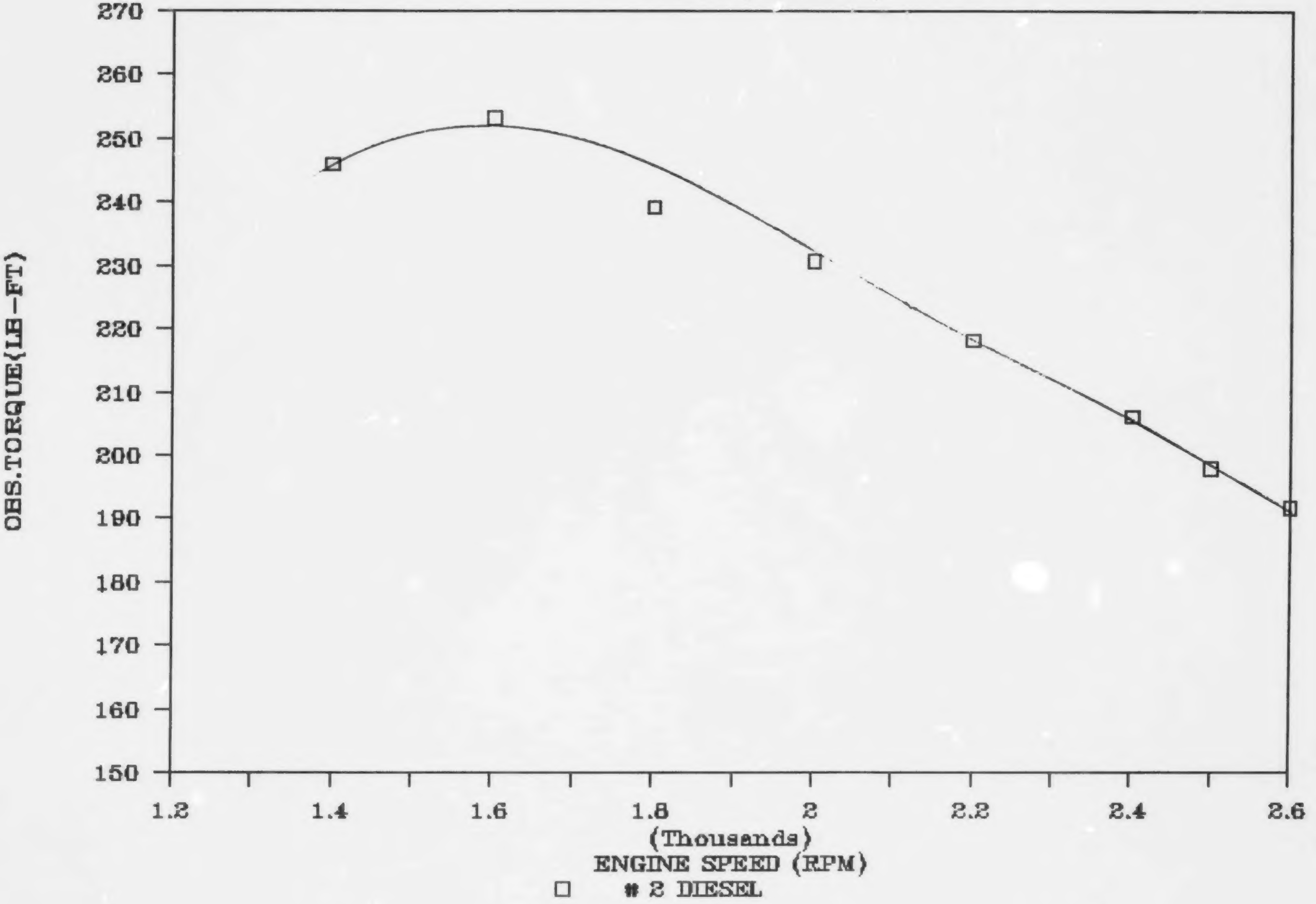
TORQUE CURVE

1 DIESEL + 2.5% DALCO



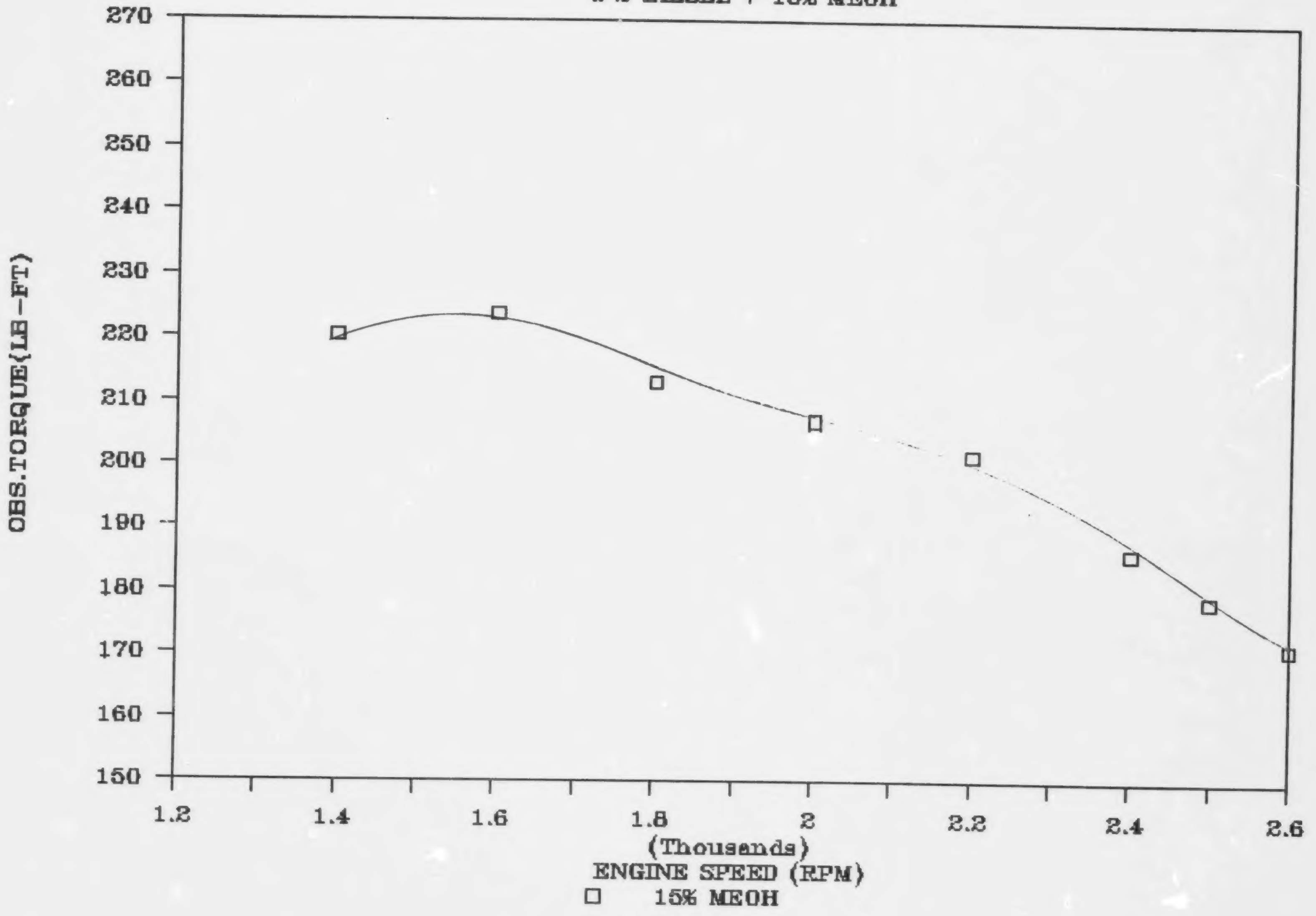
TORQUE CURVE

2 DIESEL (BASELINE)



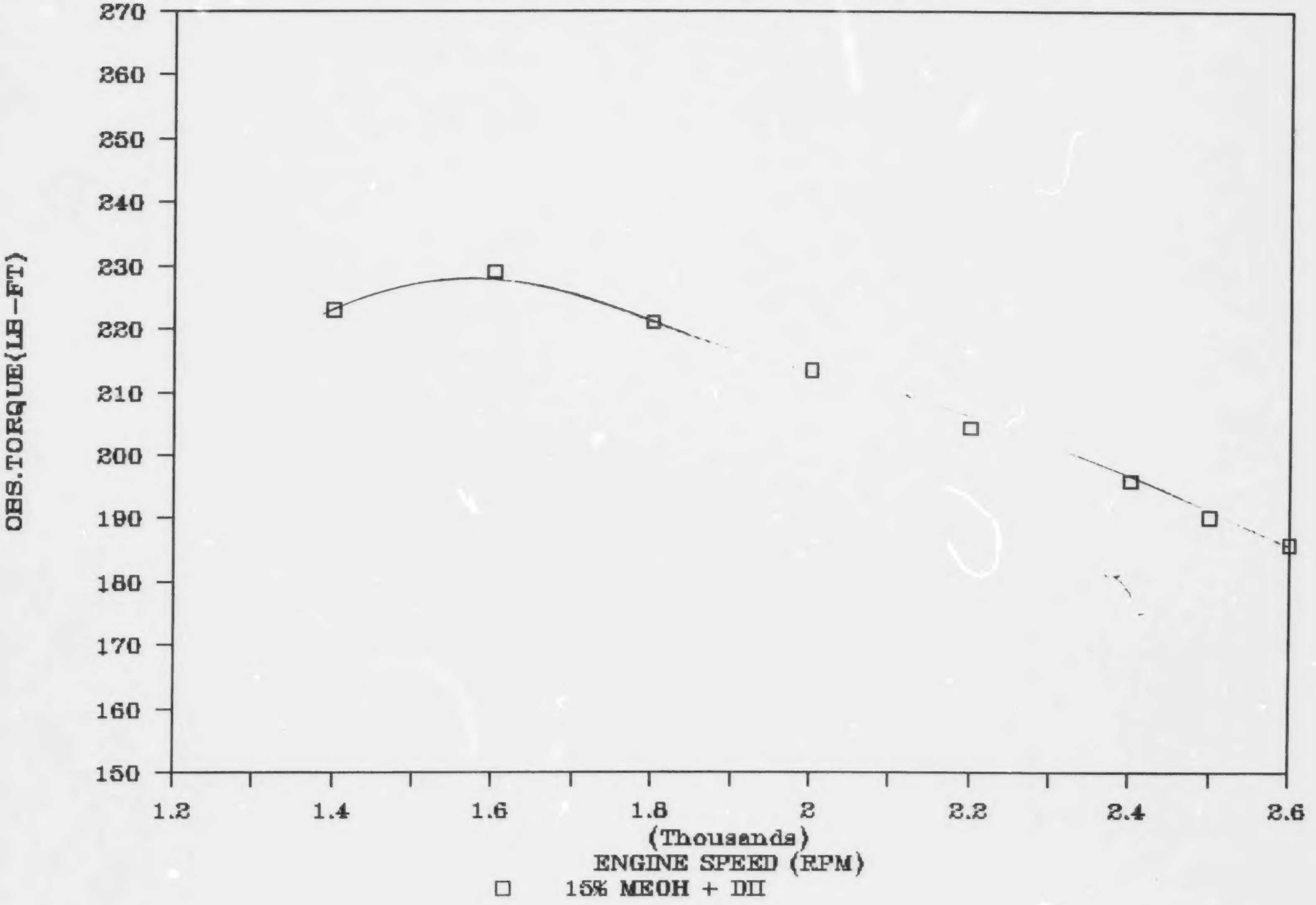
TORQUE CURVE

# 2 DIESEL + 15% MEOH



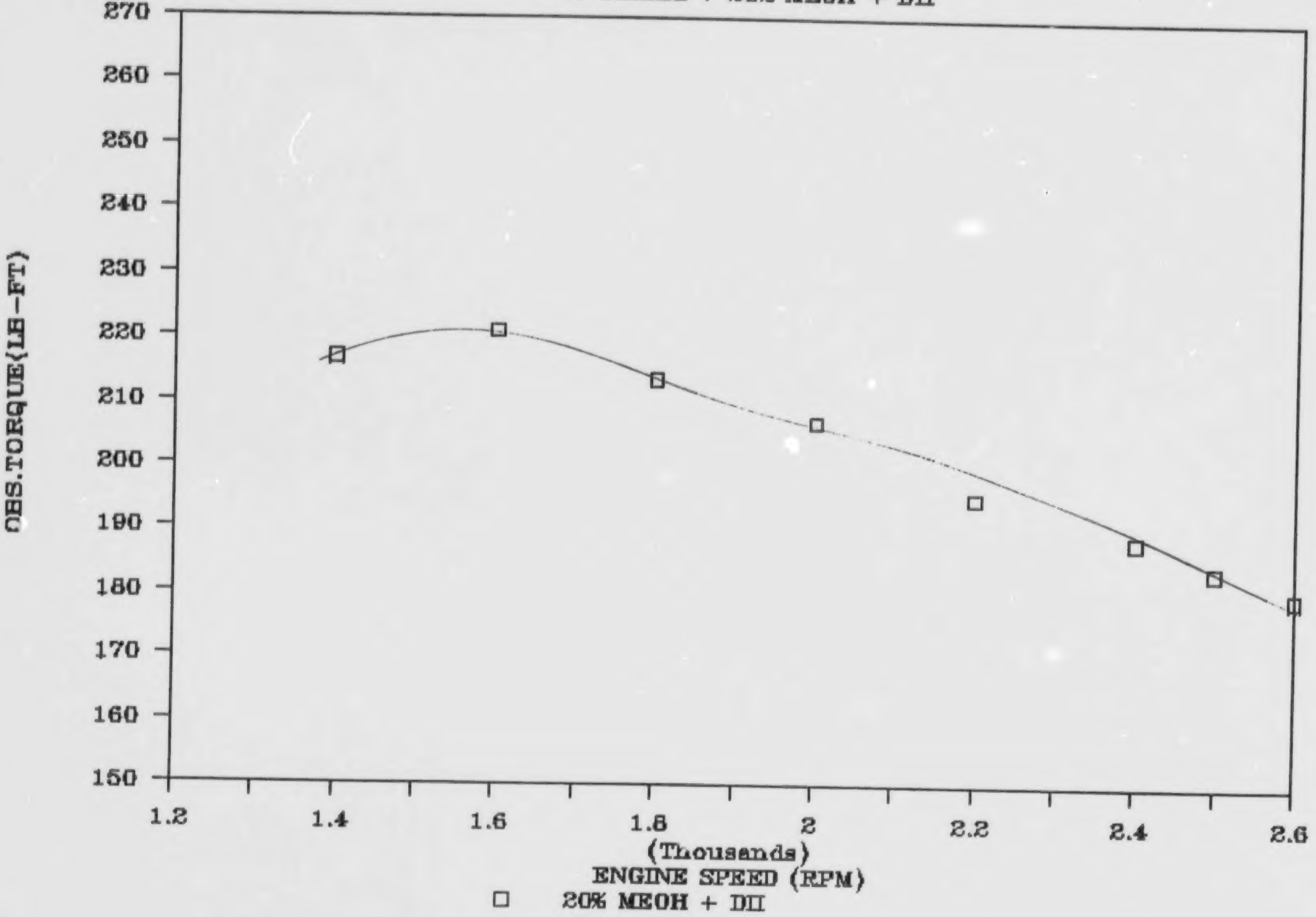
TORQUE CURVE

2 DIESEL + 15% MEOH + DII



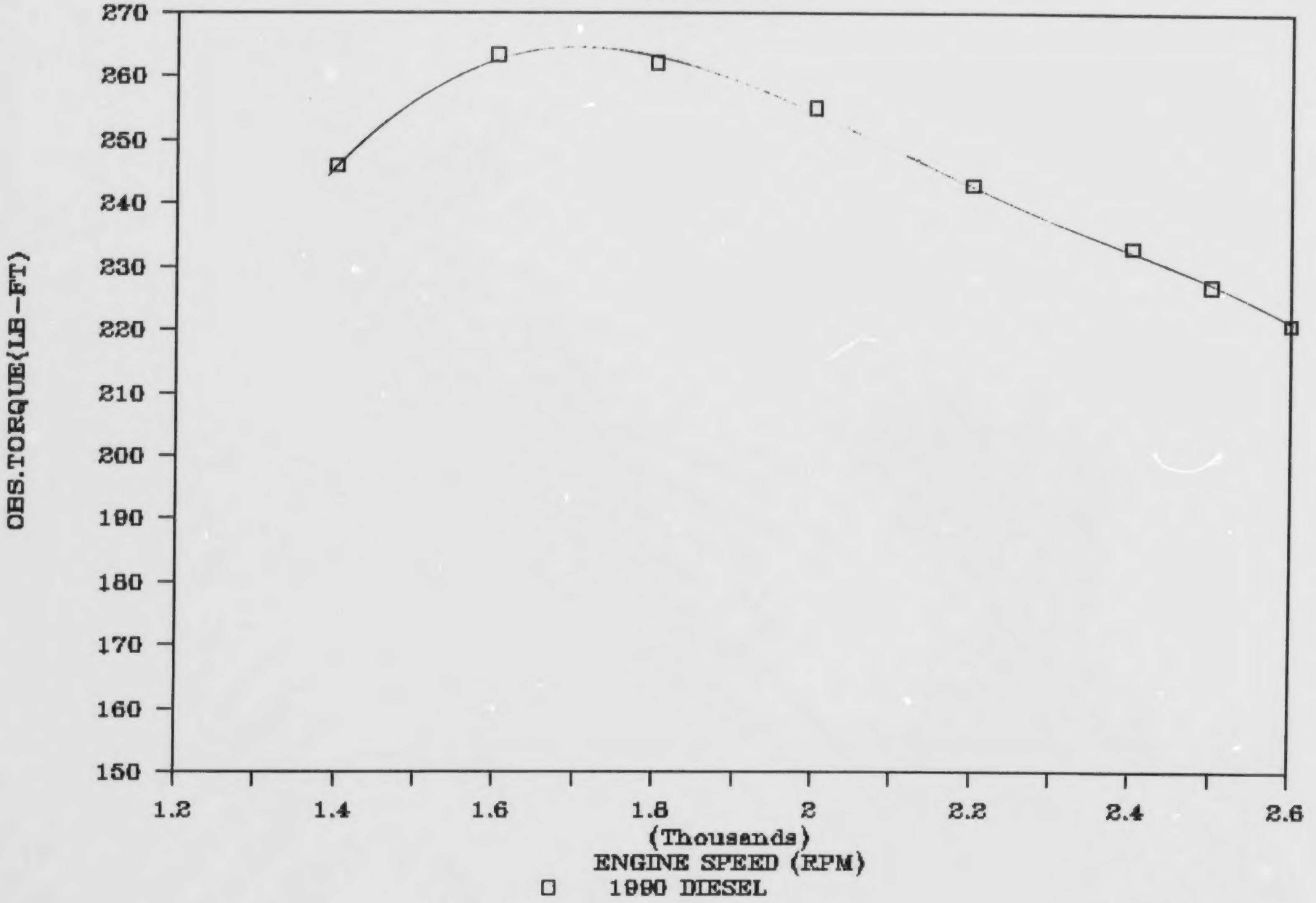
TORQUE CURVE

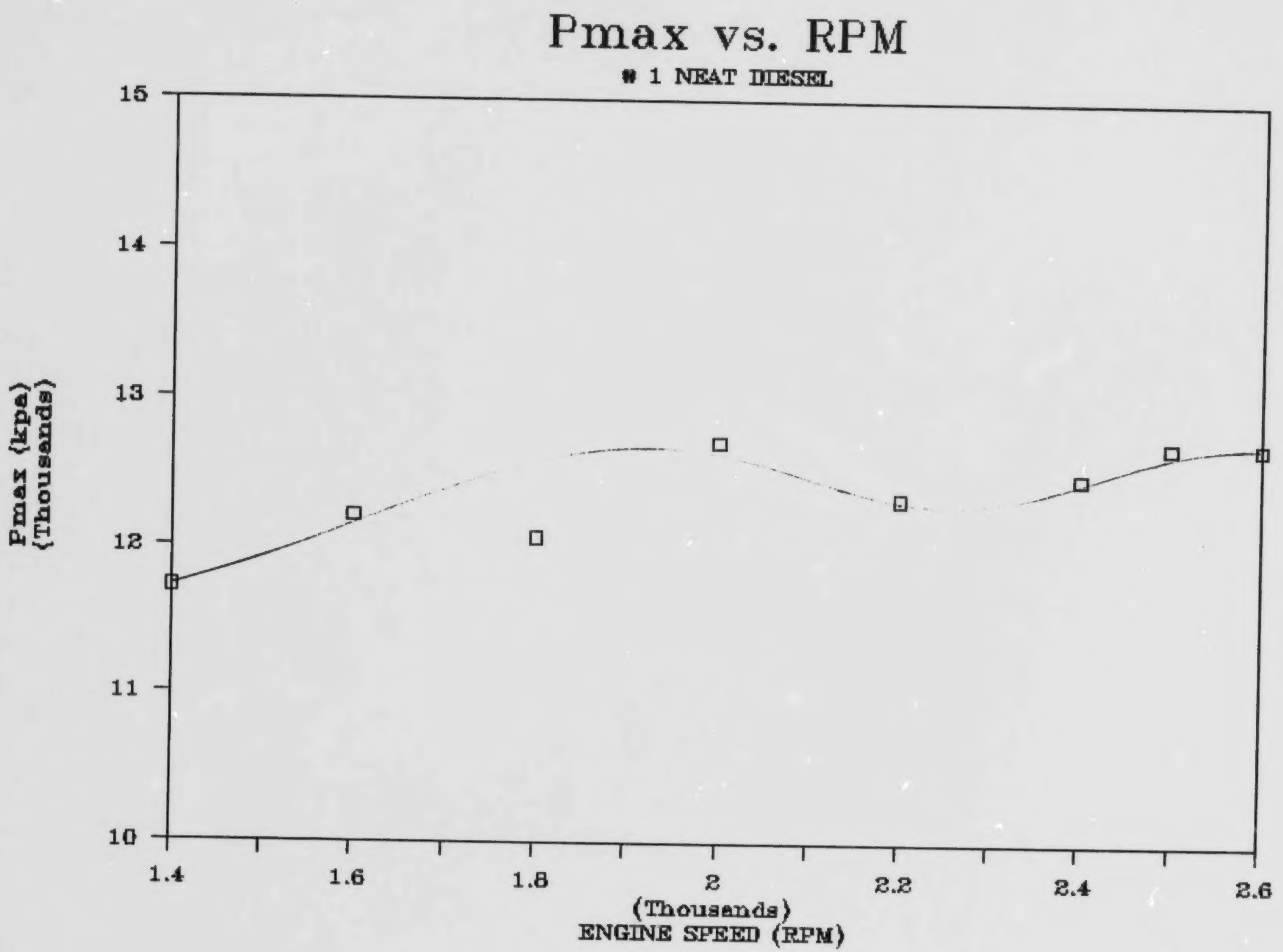
#2 DIESEL + 20% MEOH + DII



TORQUE CURVE

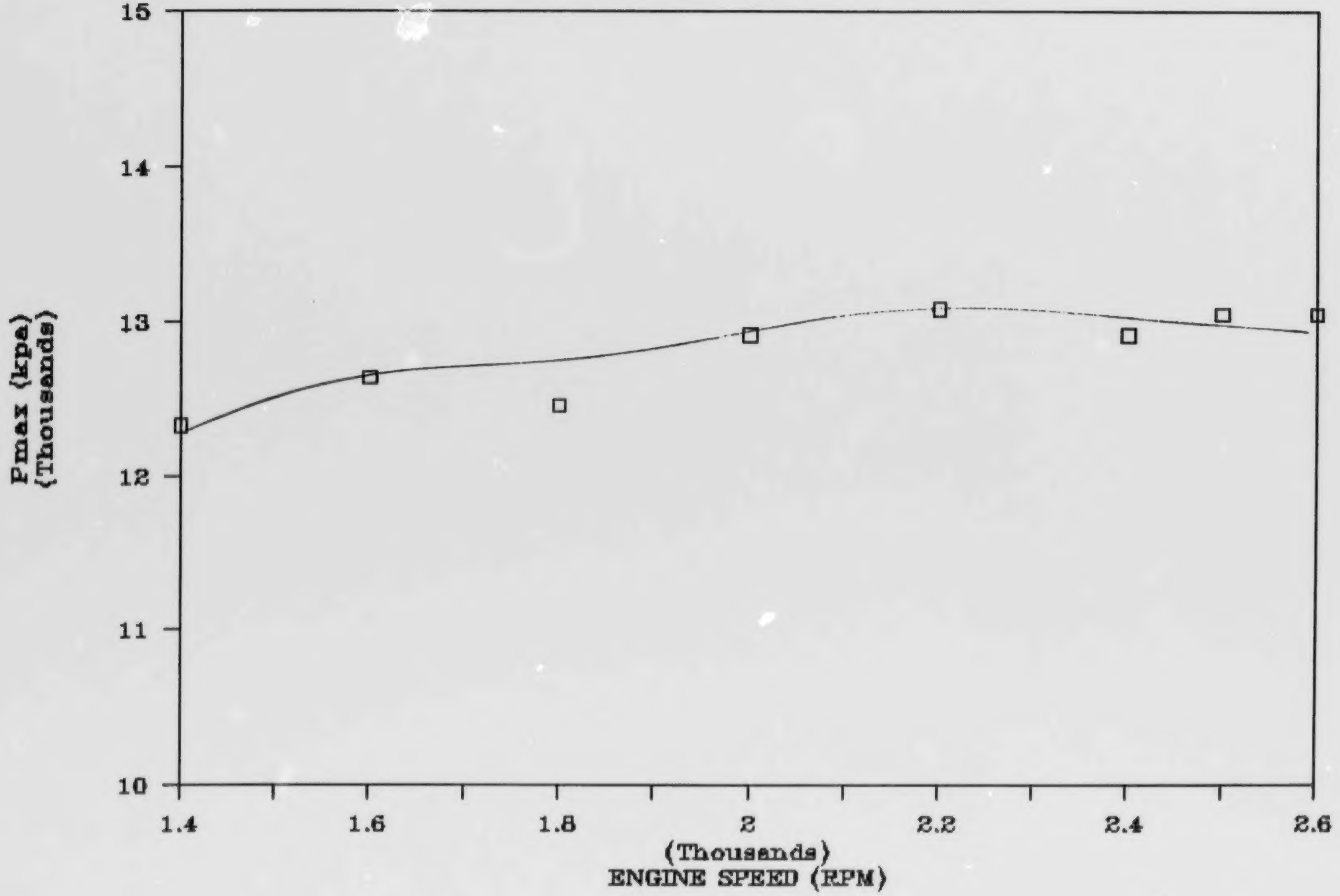
1980 DIESEL

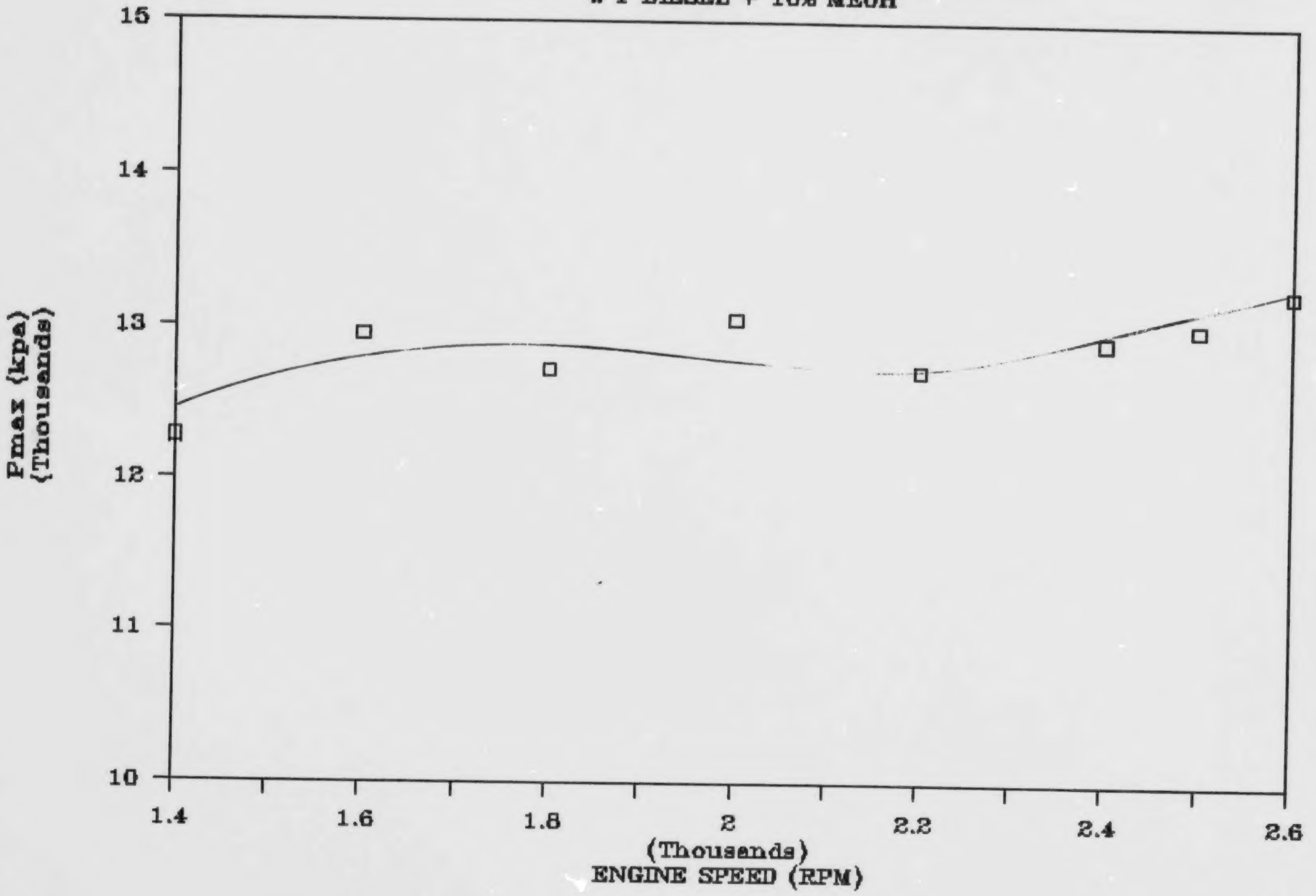



Pmax vs. RPM
# 1 NEAT DIESEL
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

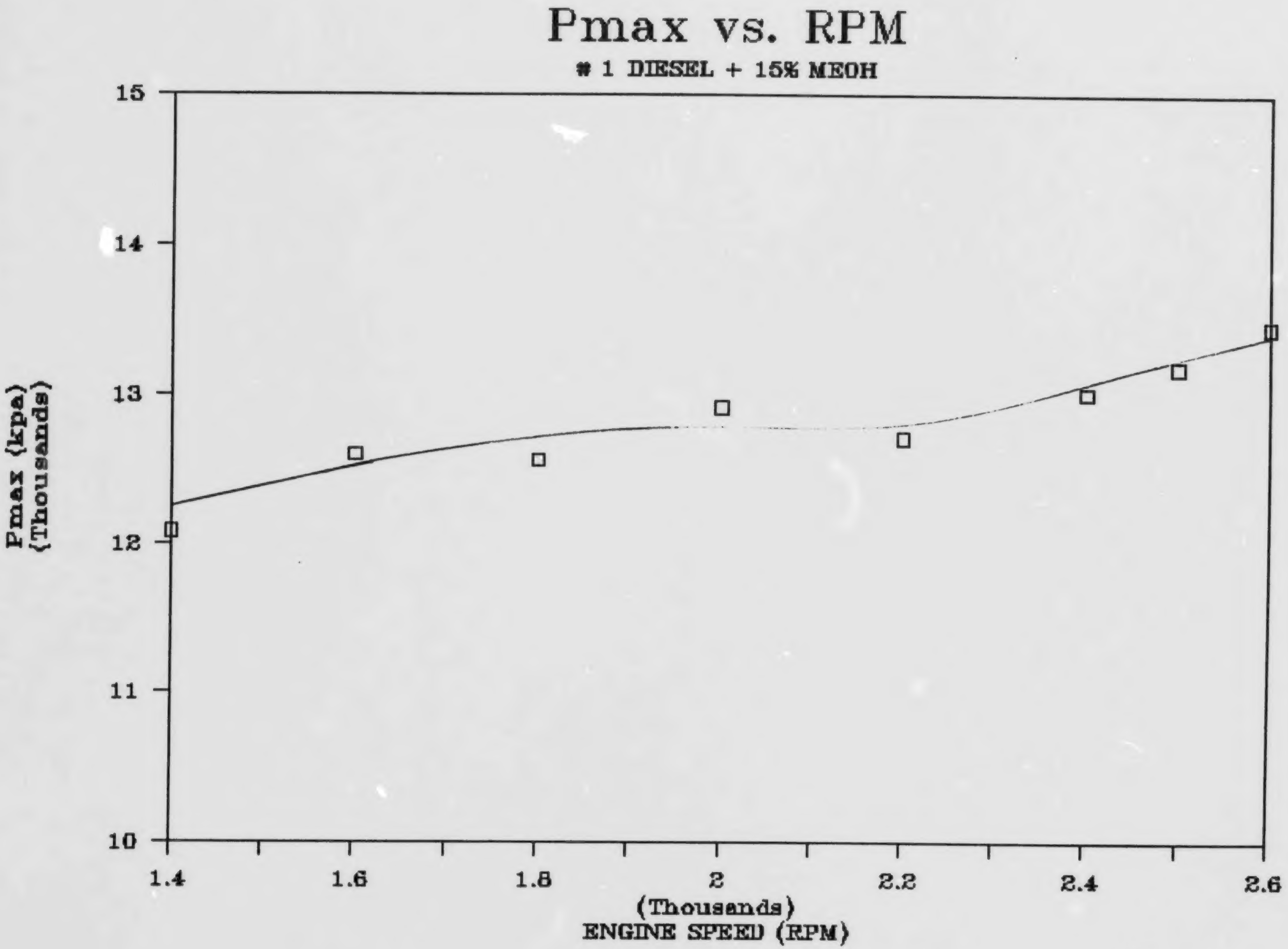
Pmax vs. RPM

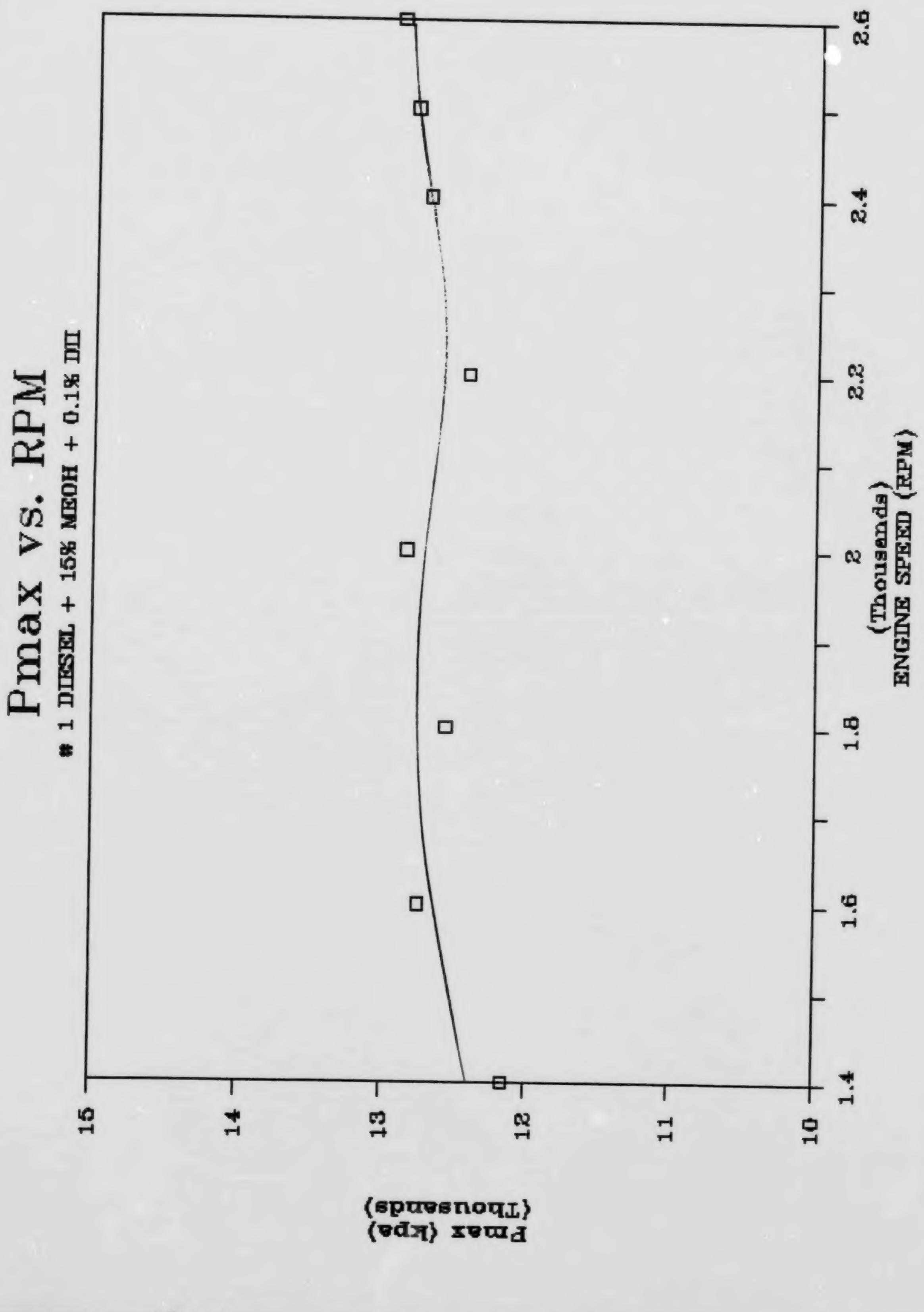
1 DIESEL + 5% METHANOL




Pmax vs. RPM

1 DIESEL + 10% MEOH


Pmax vs. RPM
# 1 DIESEL + 15% MEOH
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

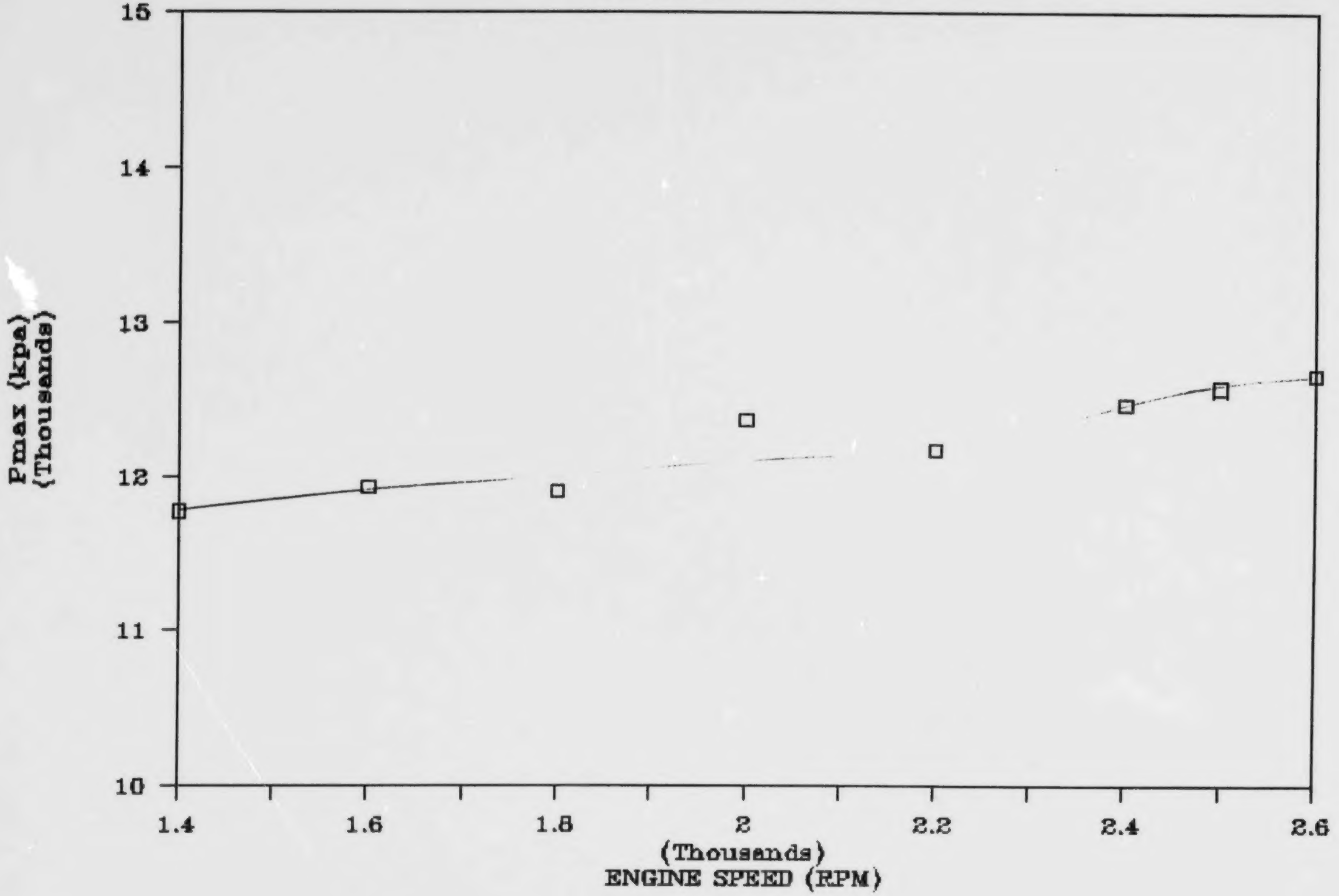


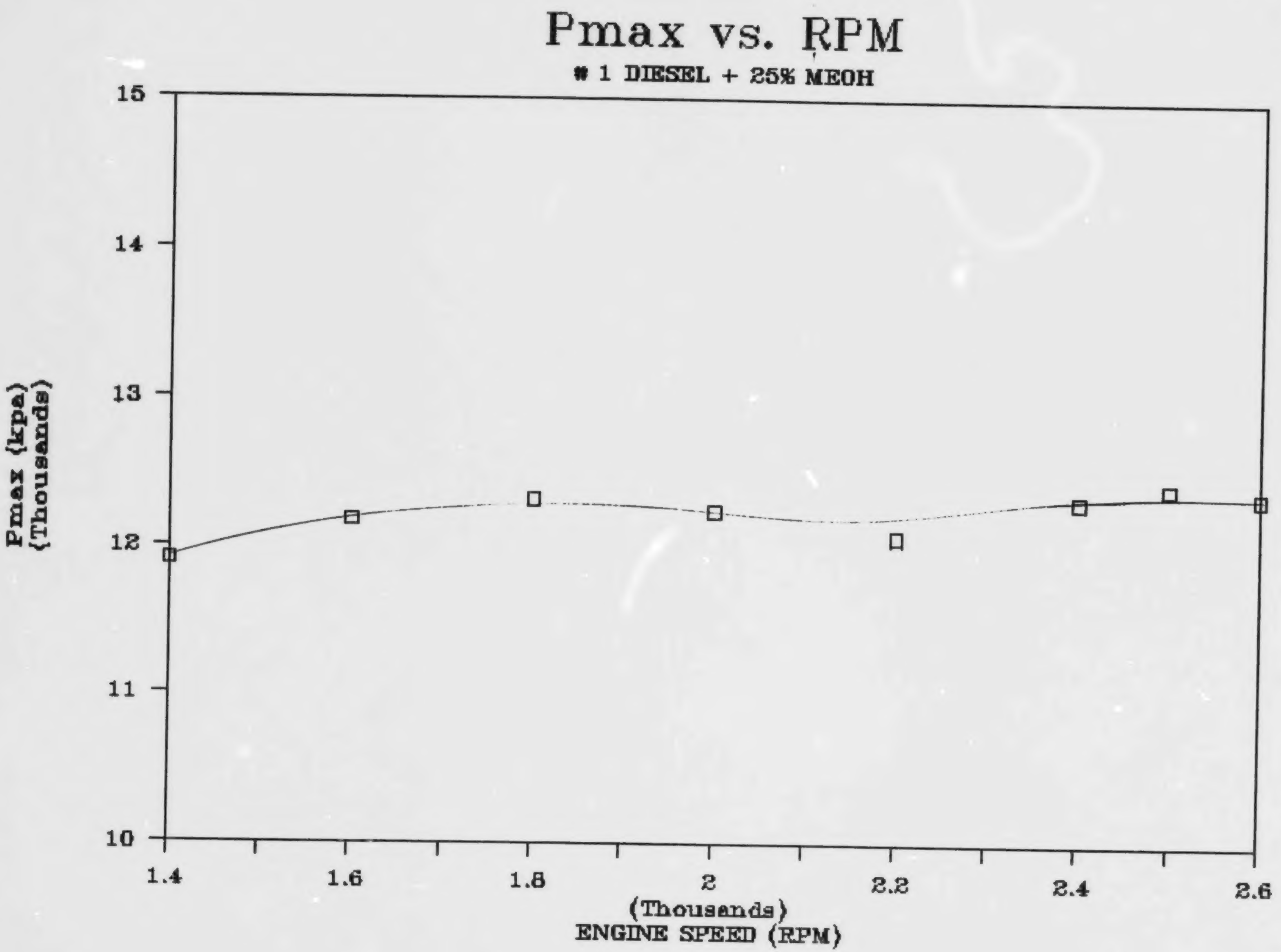
Pmax vs. RPM

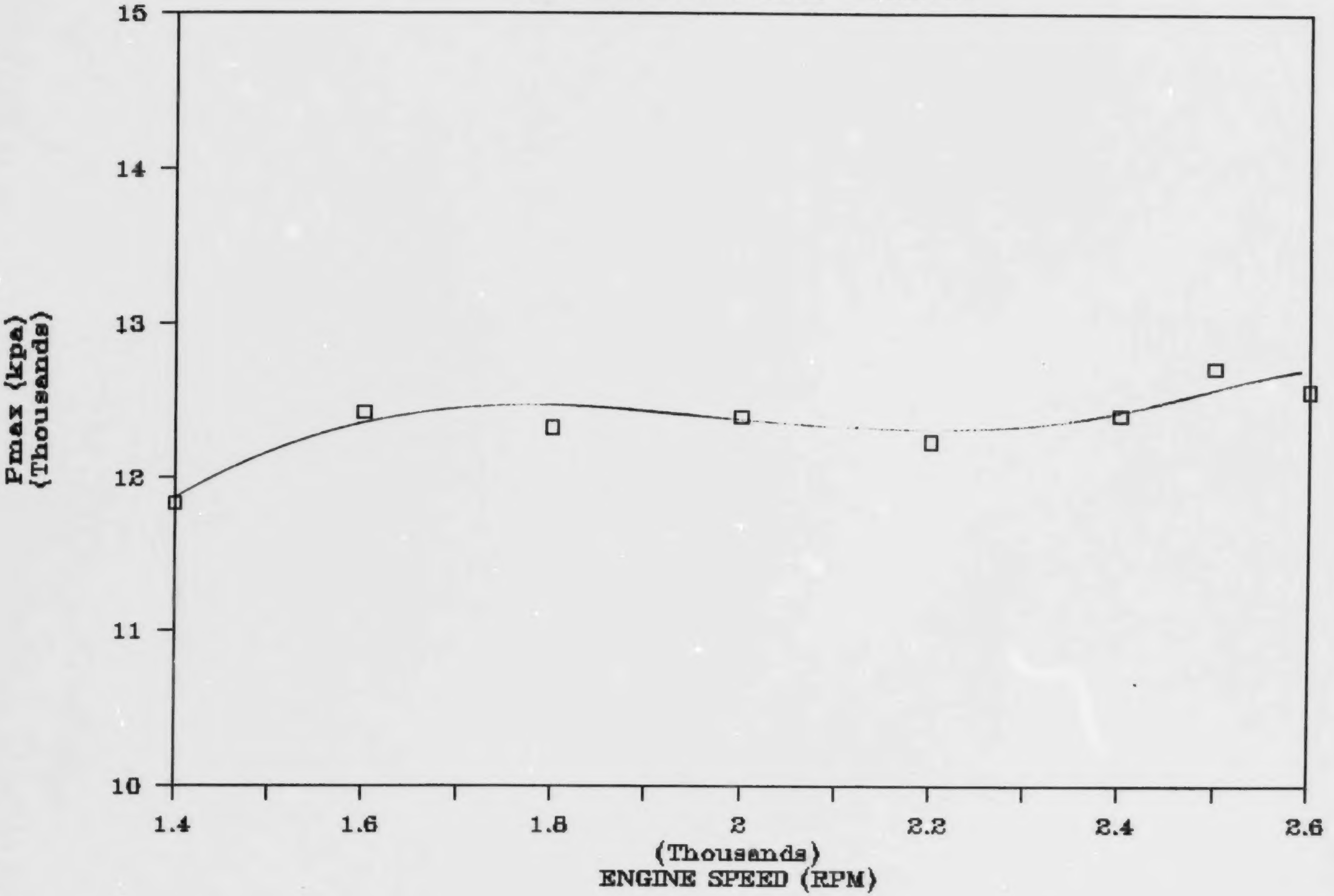
1 DIESEL + 15% MEOH + 0.1% DII

Pmax vs. RPM

1 DIESEL + 20% MEOH

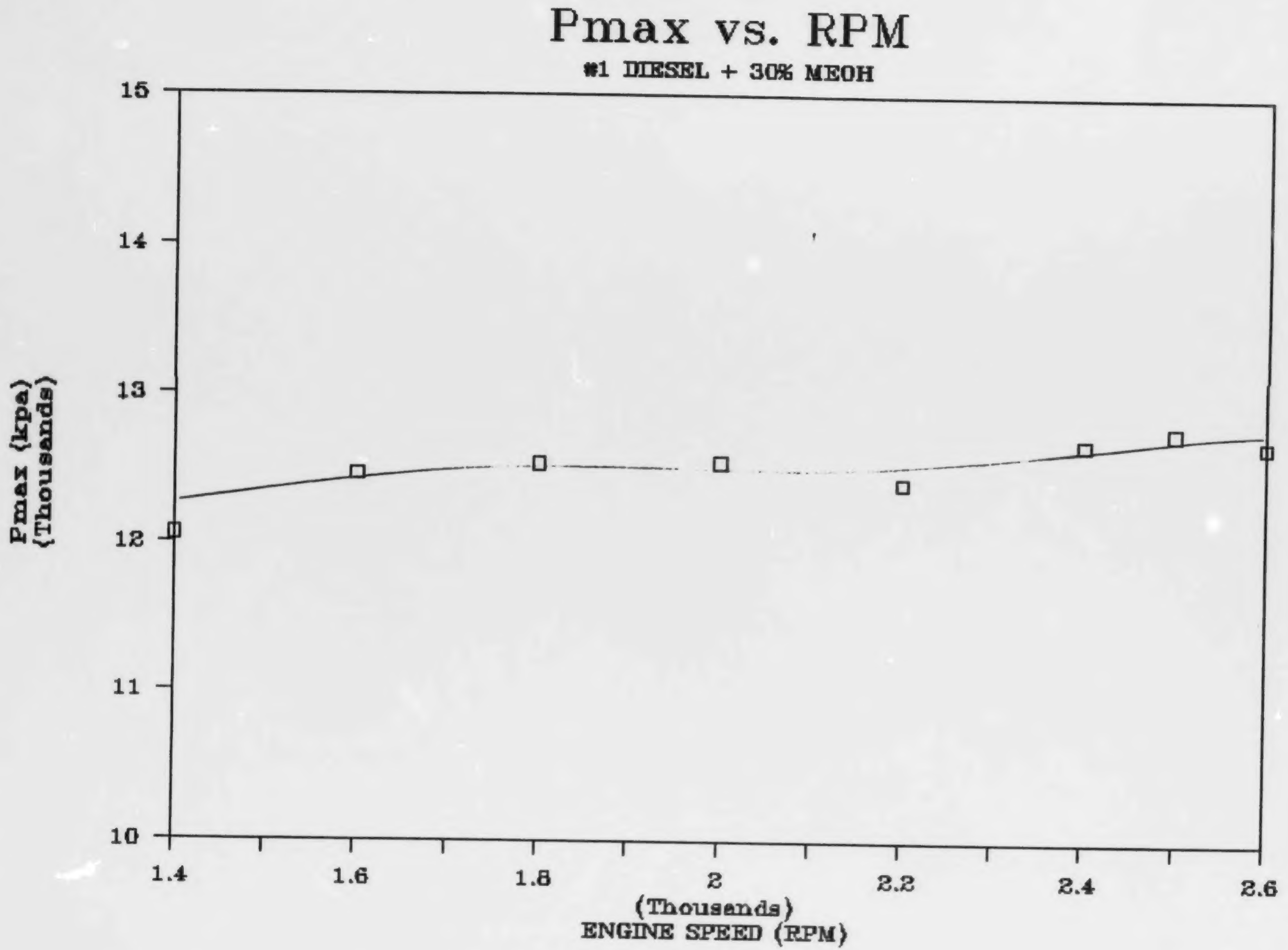


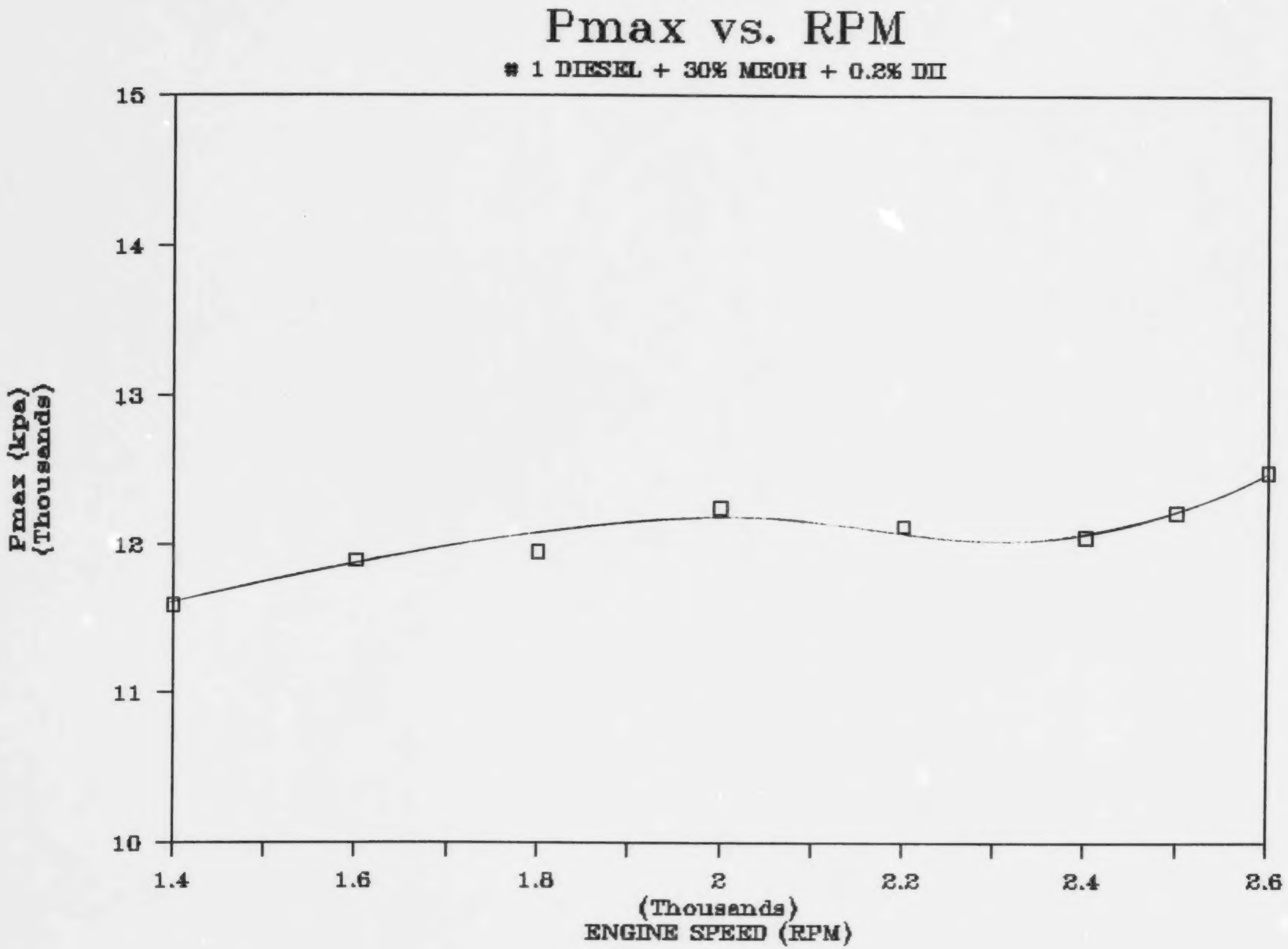

Pmax vs. RPM
# 1 DIESEL + 25% MEOH
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

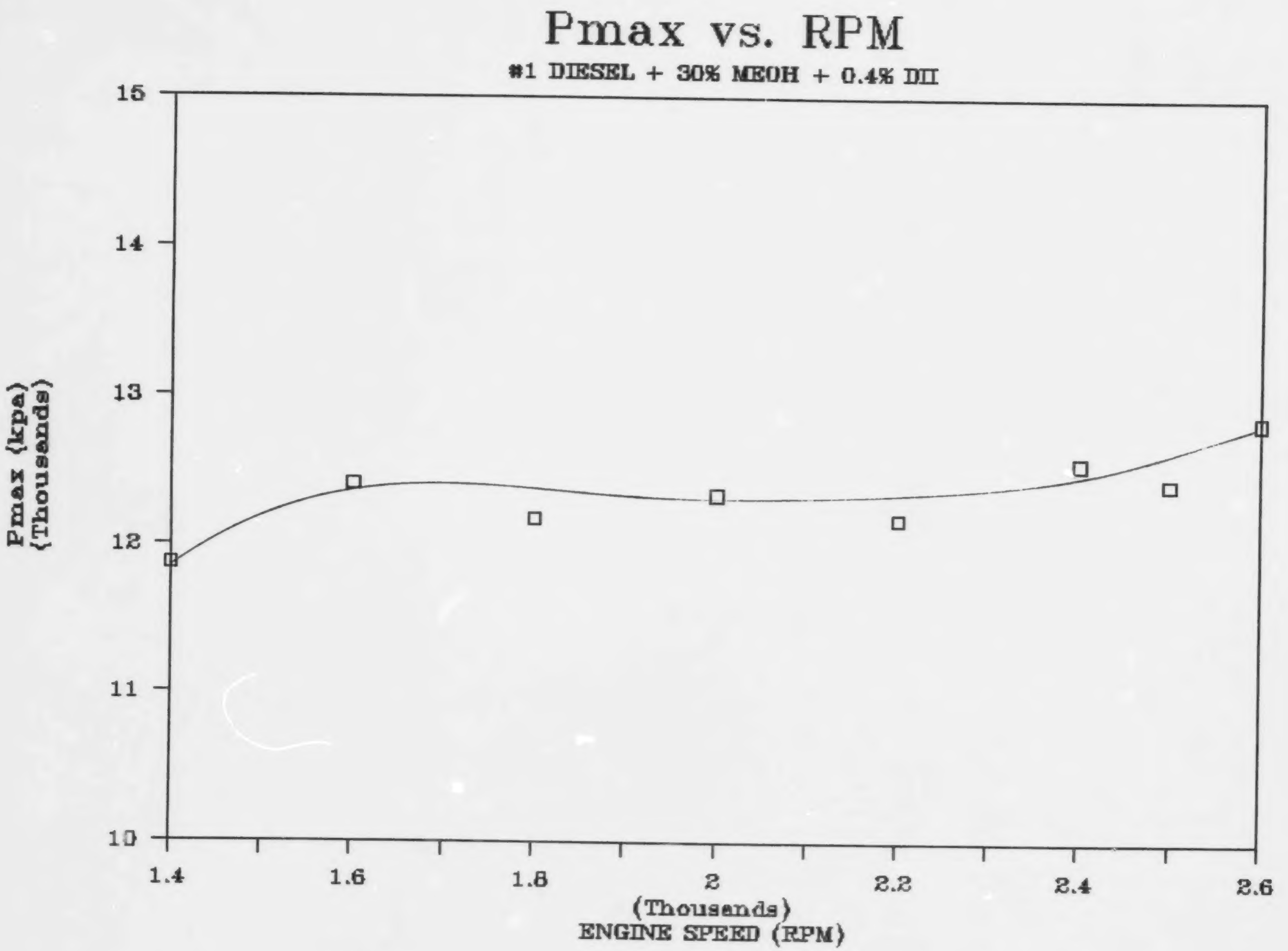


Pmax vs. RPM

#1 DIESEL + 25% MEOH + 0.2% DII


Pmax vs. RPM
#1 DIESEL + 30% MEOH
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)


Pmax vs. RPM
# 1 DIESEL + 30% MEOH + 0.2% DII
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)


Pmax vs. RPM

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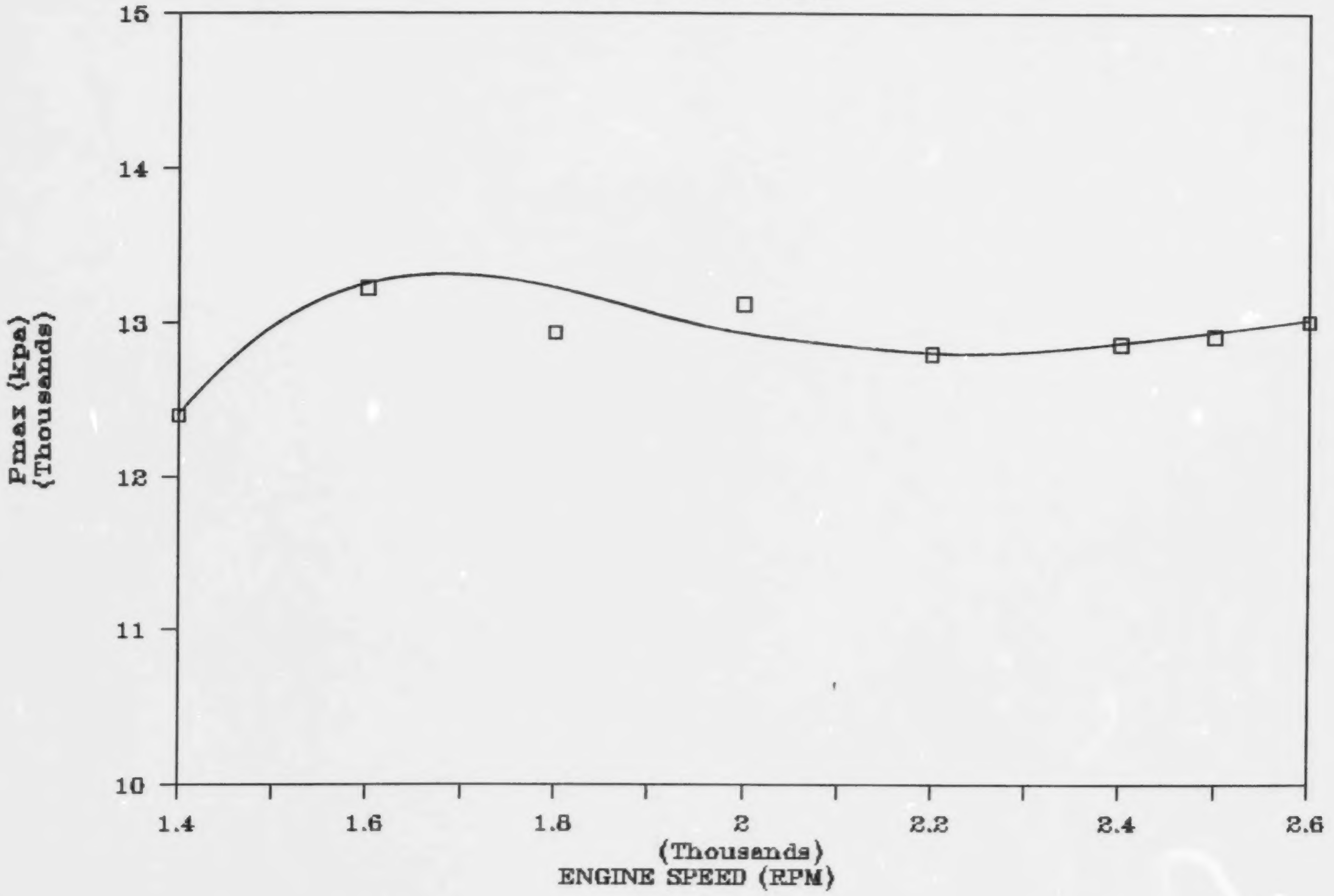
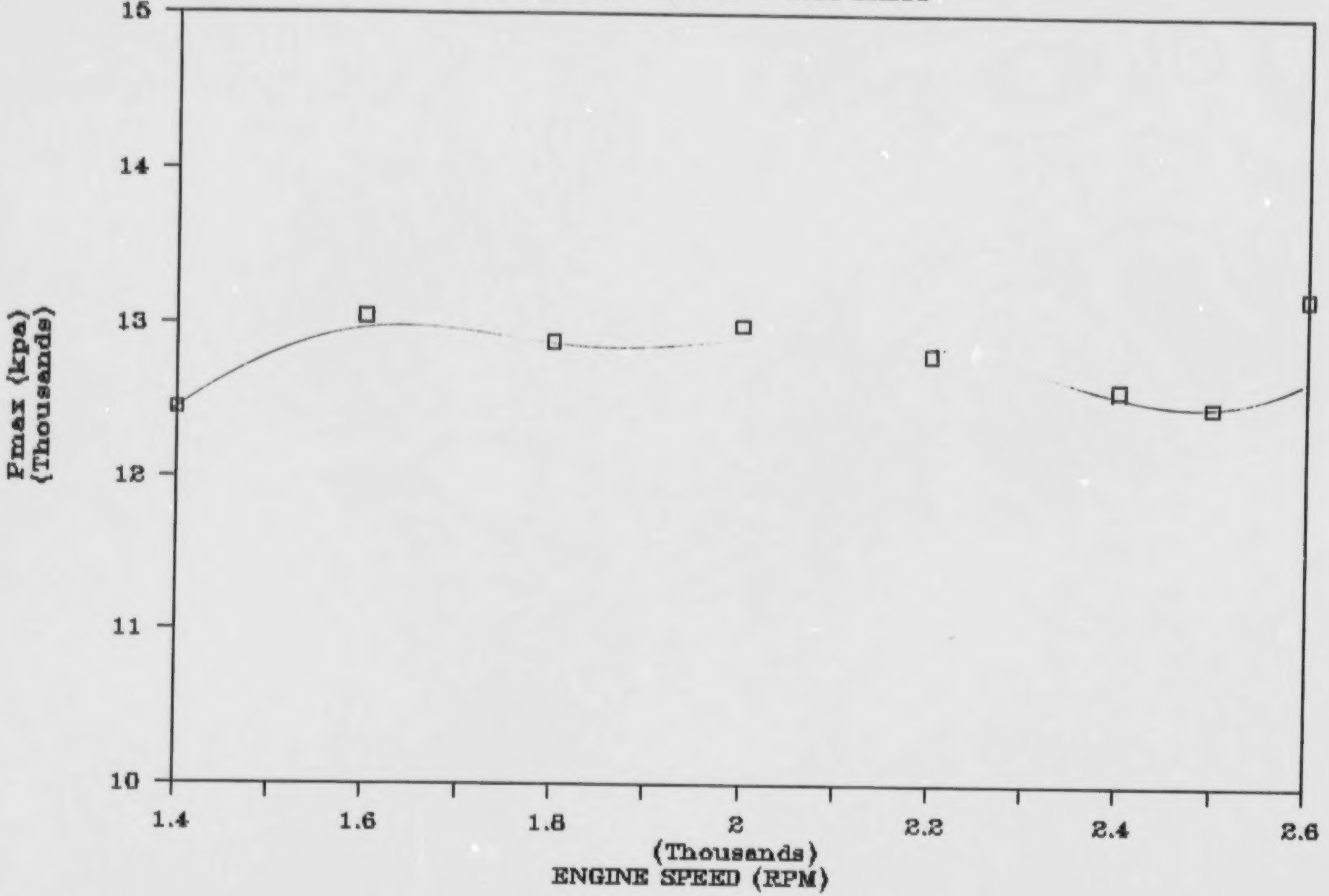


Pmax vs. RPM

#1 DIESEL + 5% H20

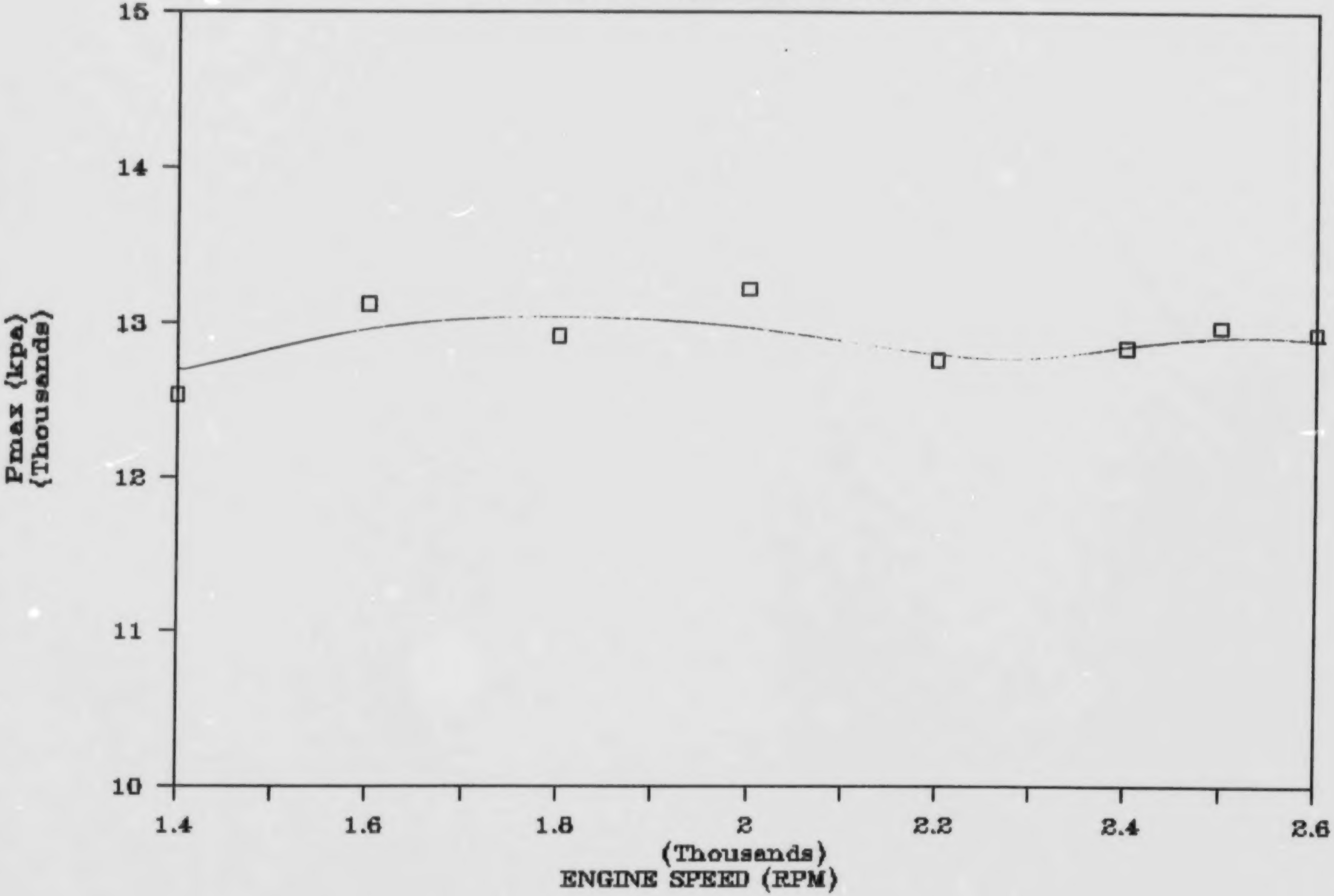
Pmax vs. RPM

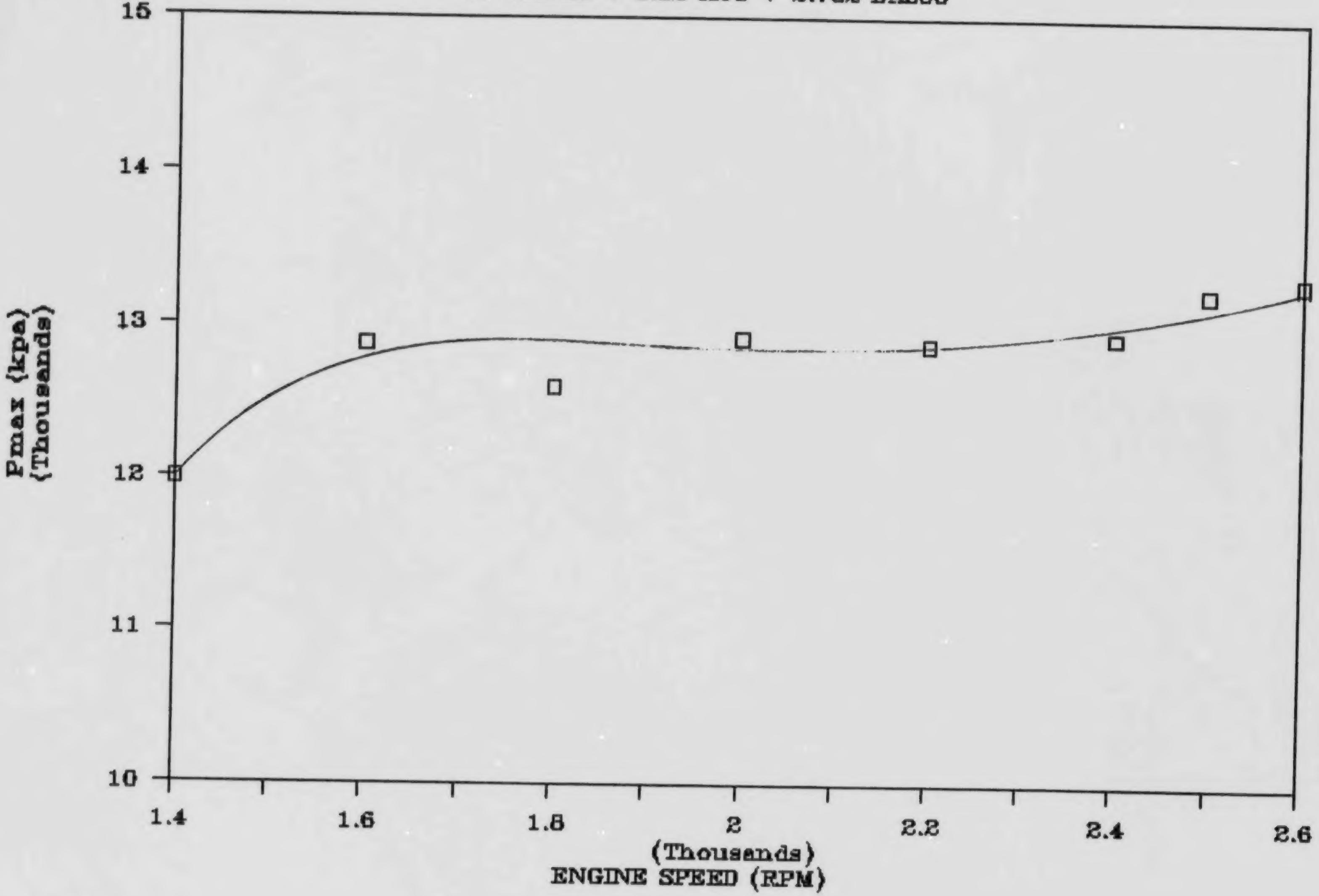
#1 DIESEL + 5% H20 + 2.5% DALCO



Pmax vs. RPM

#1 + 5% H20 + 2.5% DALCO + 0.15% DII





Pmax vs. RPM

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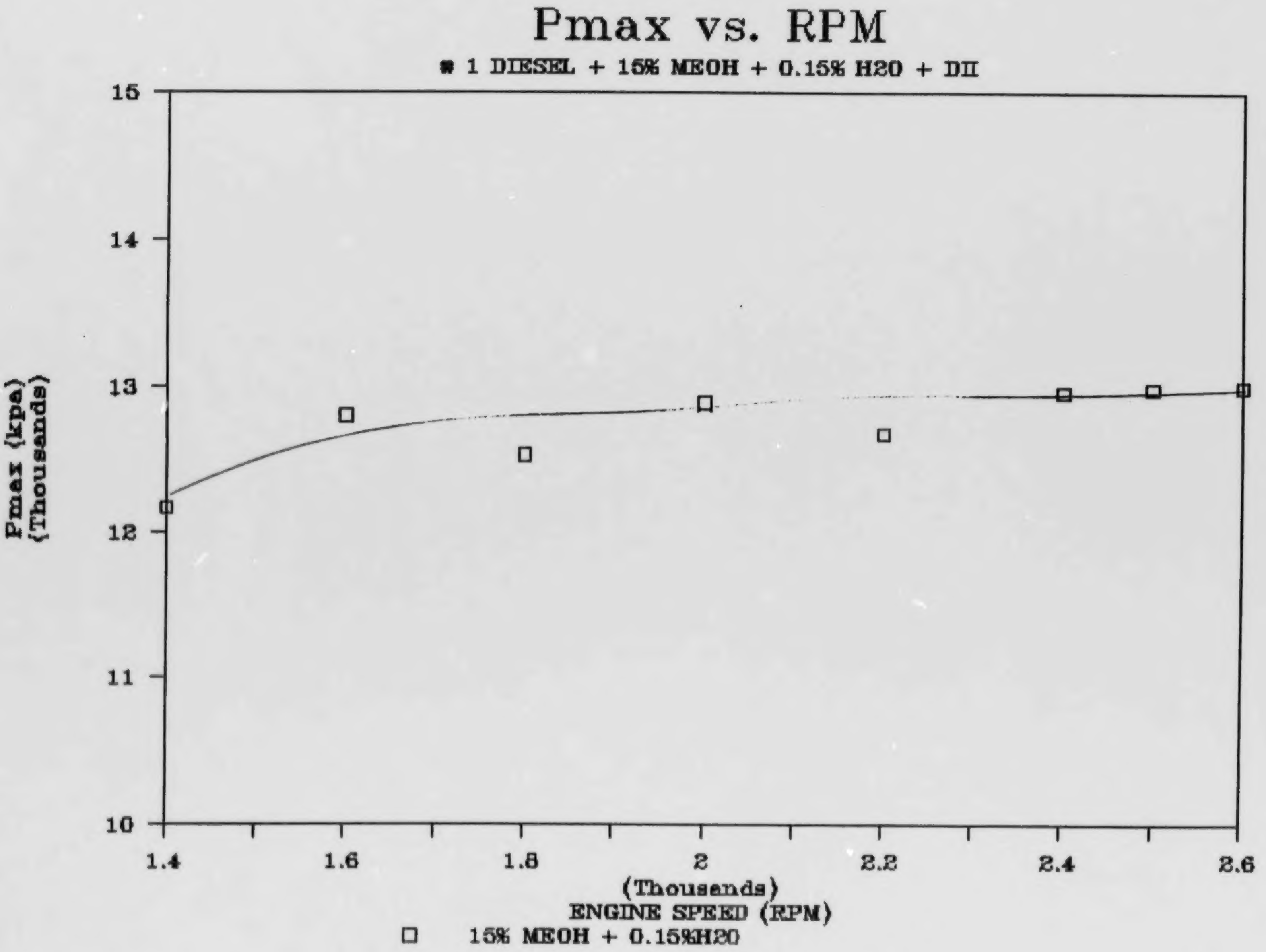
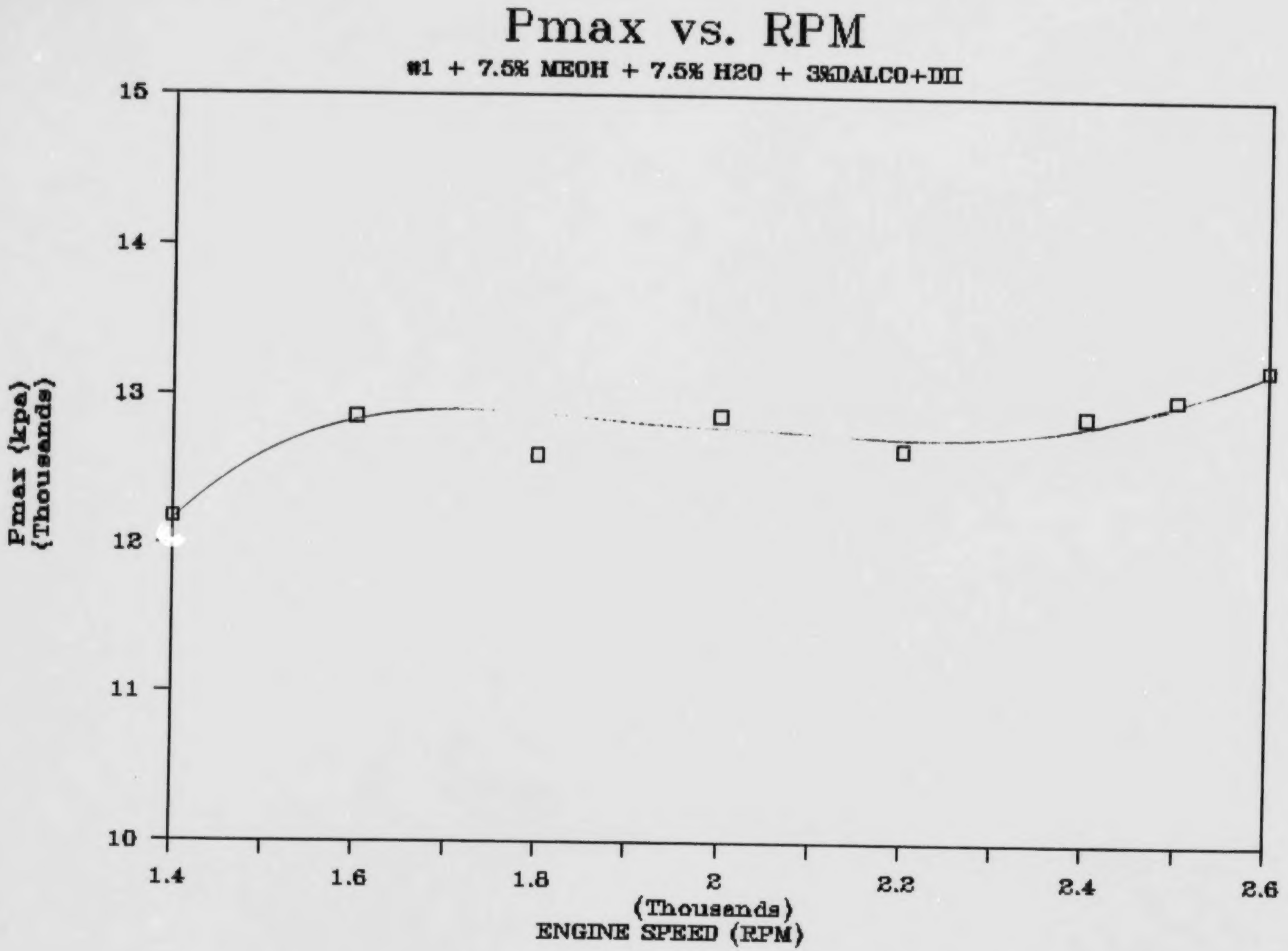
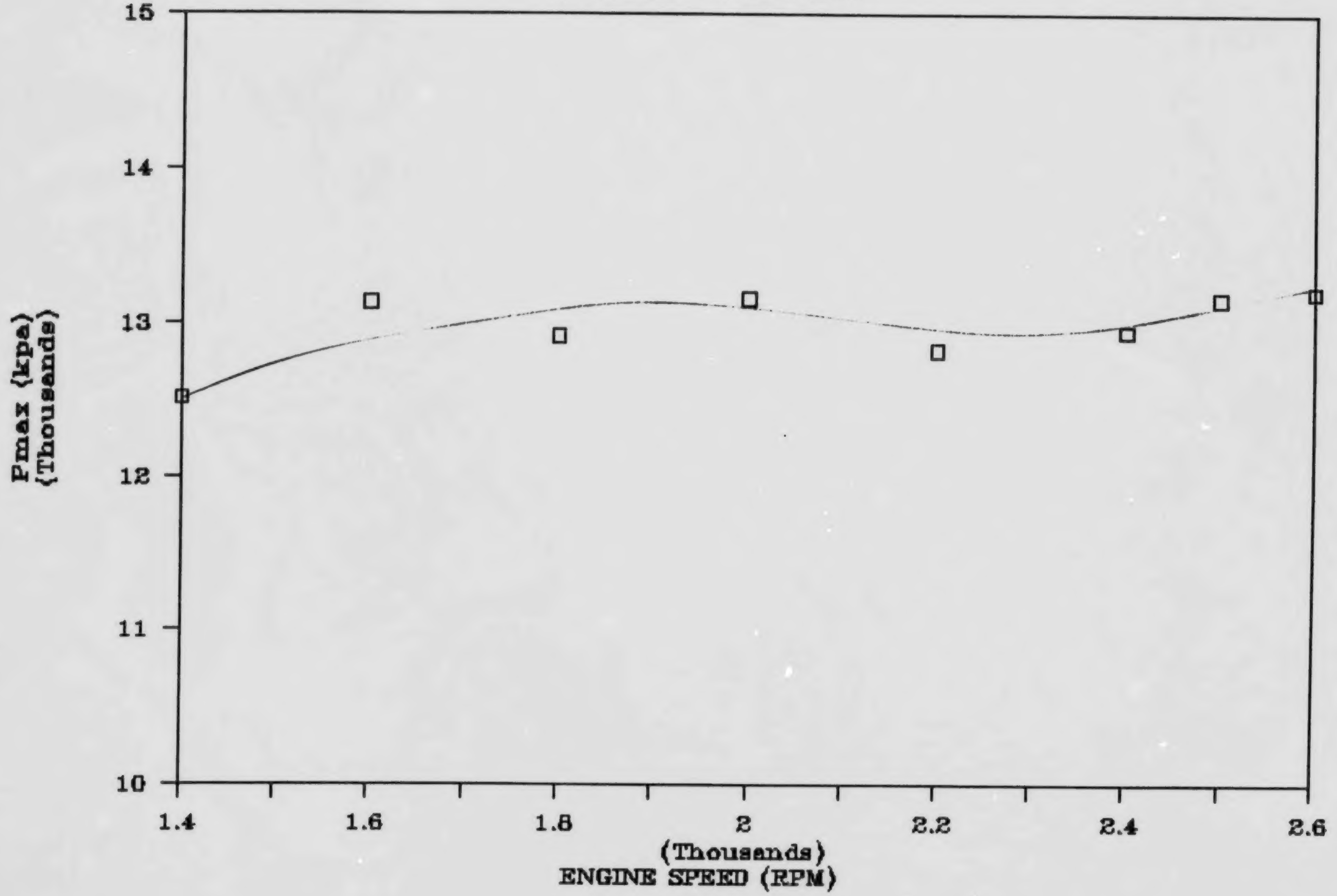
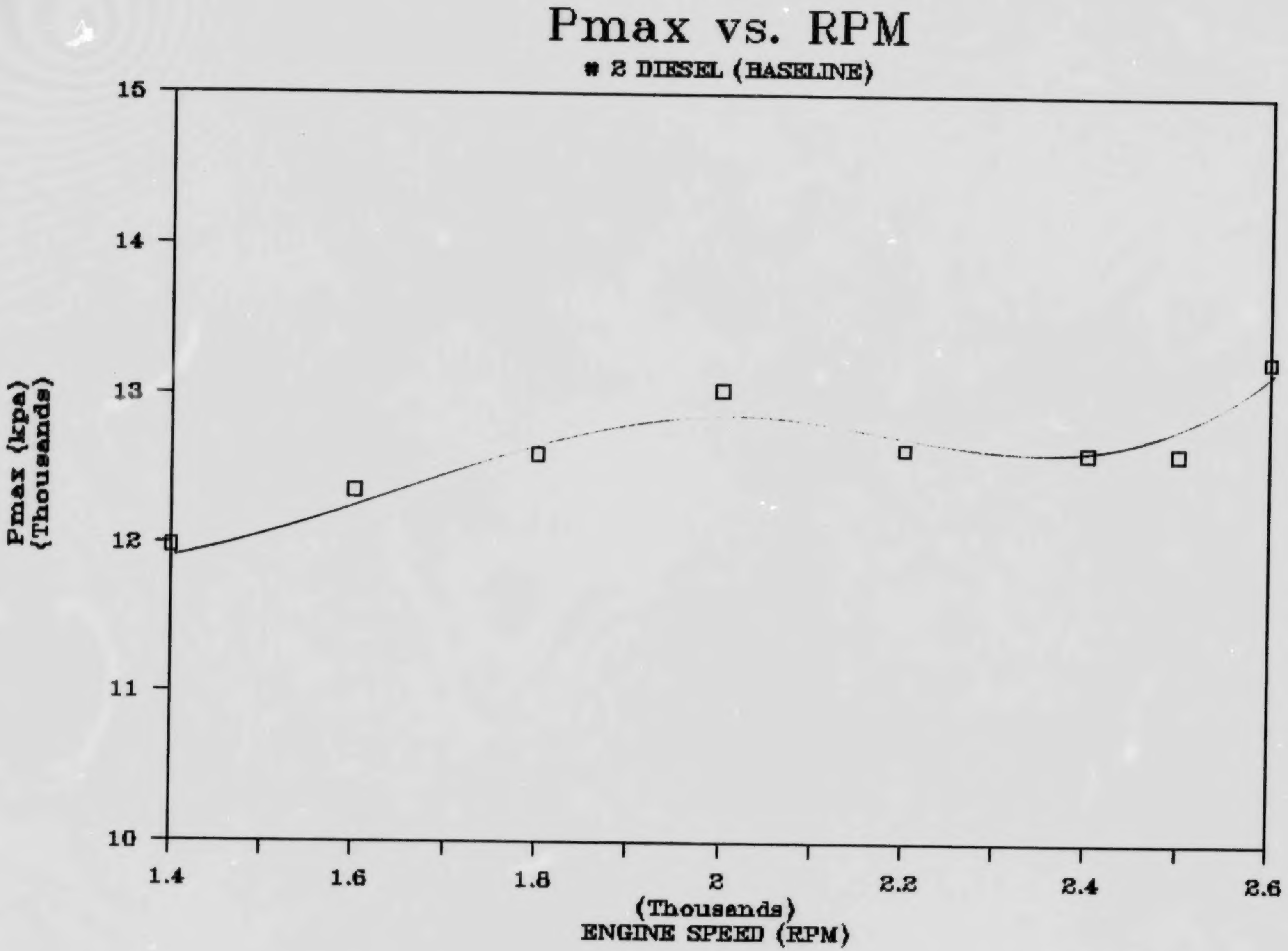

Pmax vs. RPM
# 1 DIESEL + 15% MEOH + 0.15% H2O + DII
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)
□ 15% MEOH + 0.15%H2O


Pmax vs. RPM
#1 + 7.5% MEOH + 7.5% H20 + 3%DALCO+DII
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)



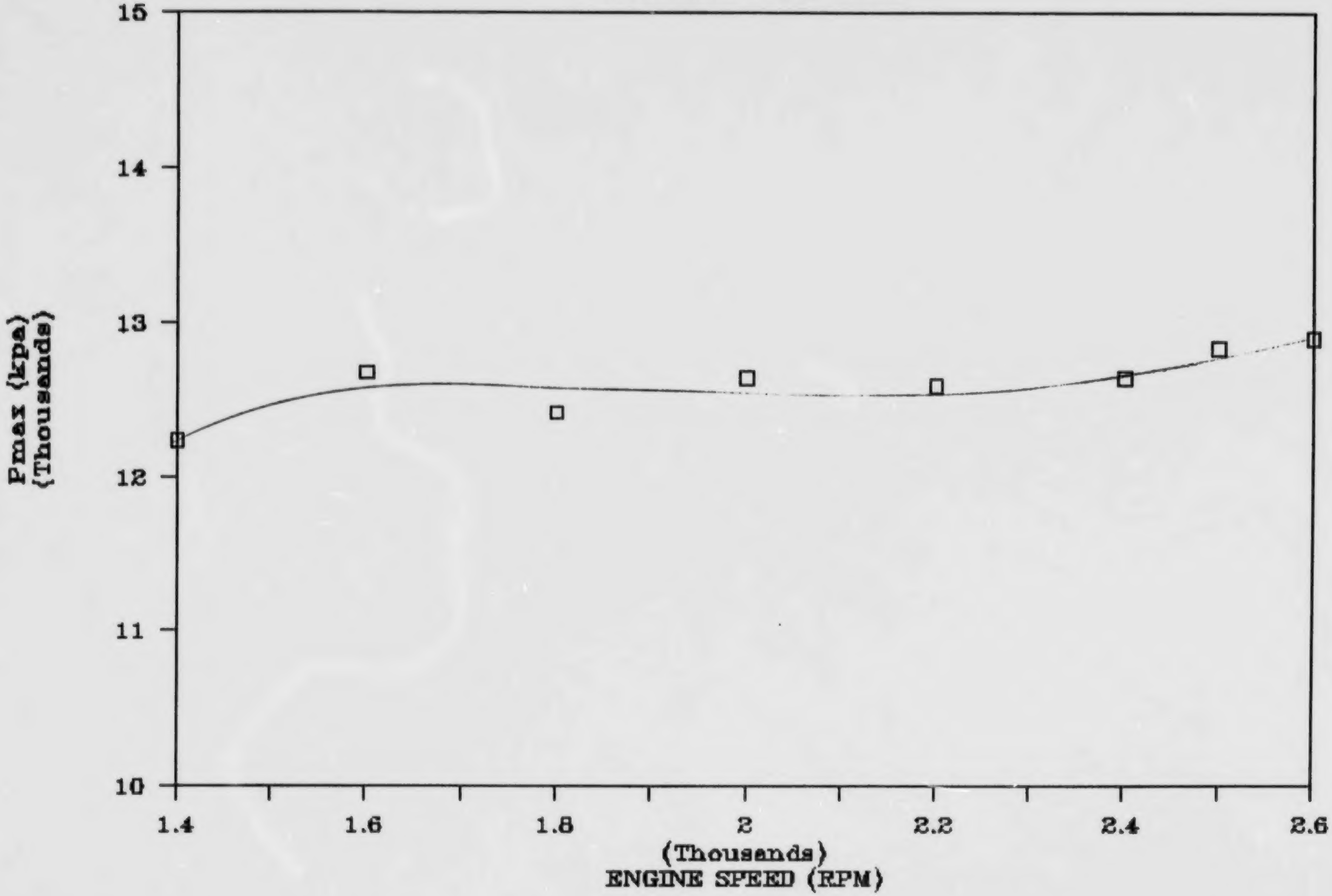
Pmax vs. RPM

#1 DIESEL + 2.5% DALCO


Pmax vs. RPM
# 2 DIESEL (BASELINE)
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

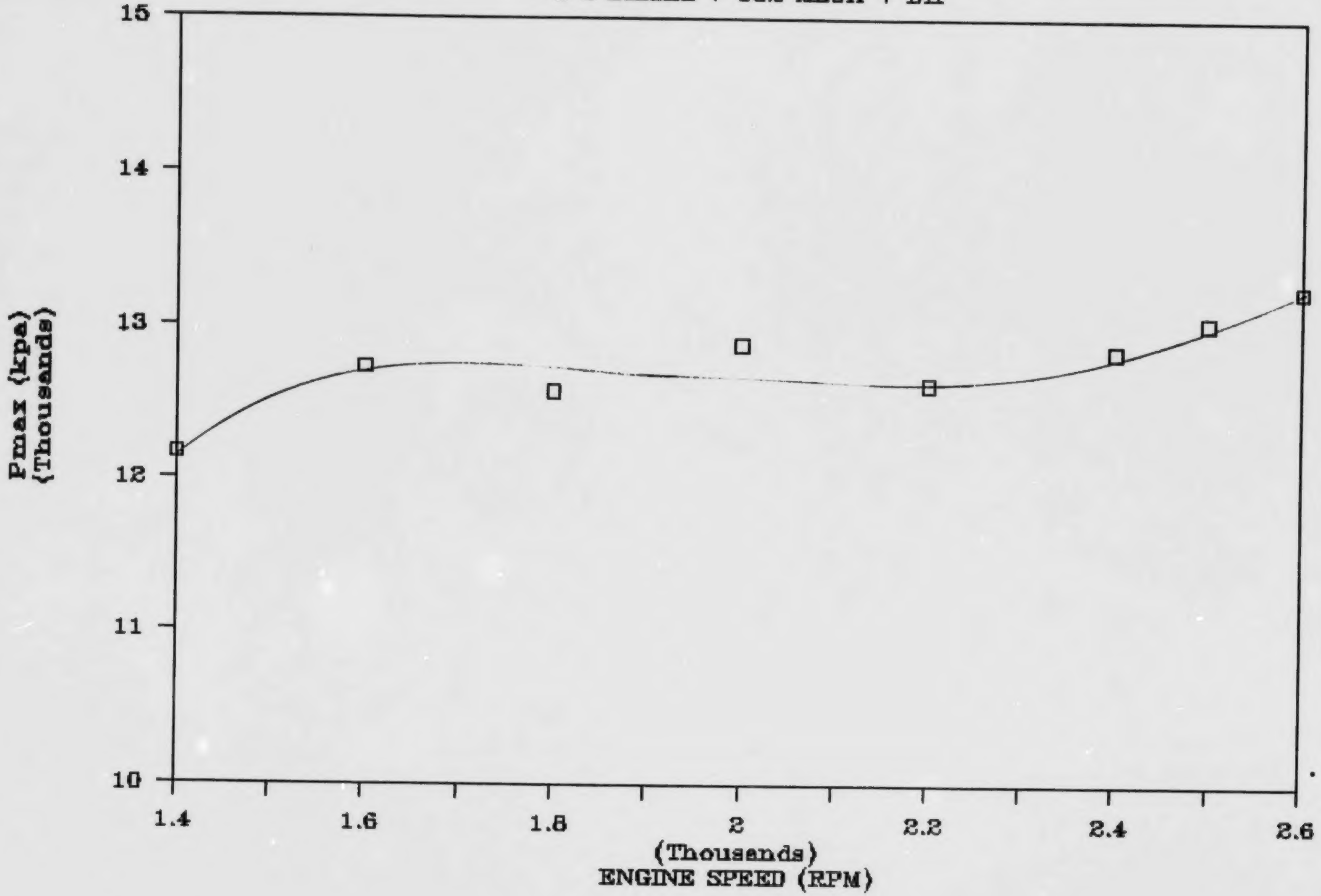
Pmax vs. RPM

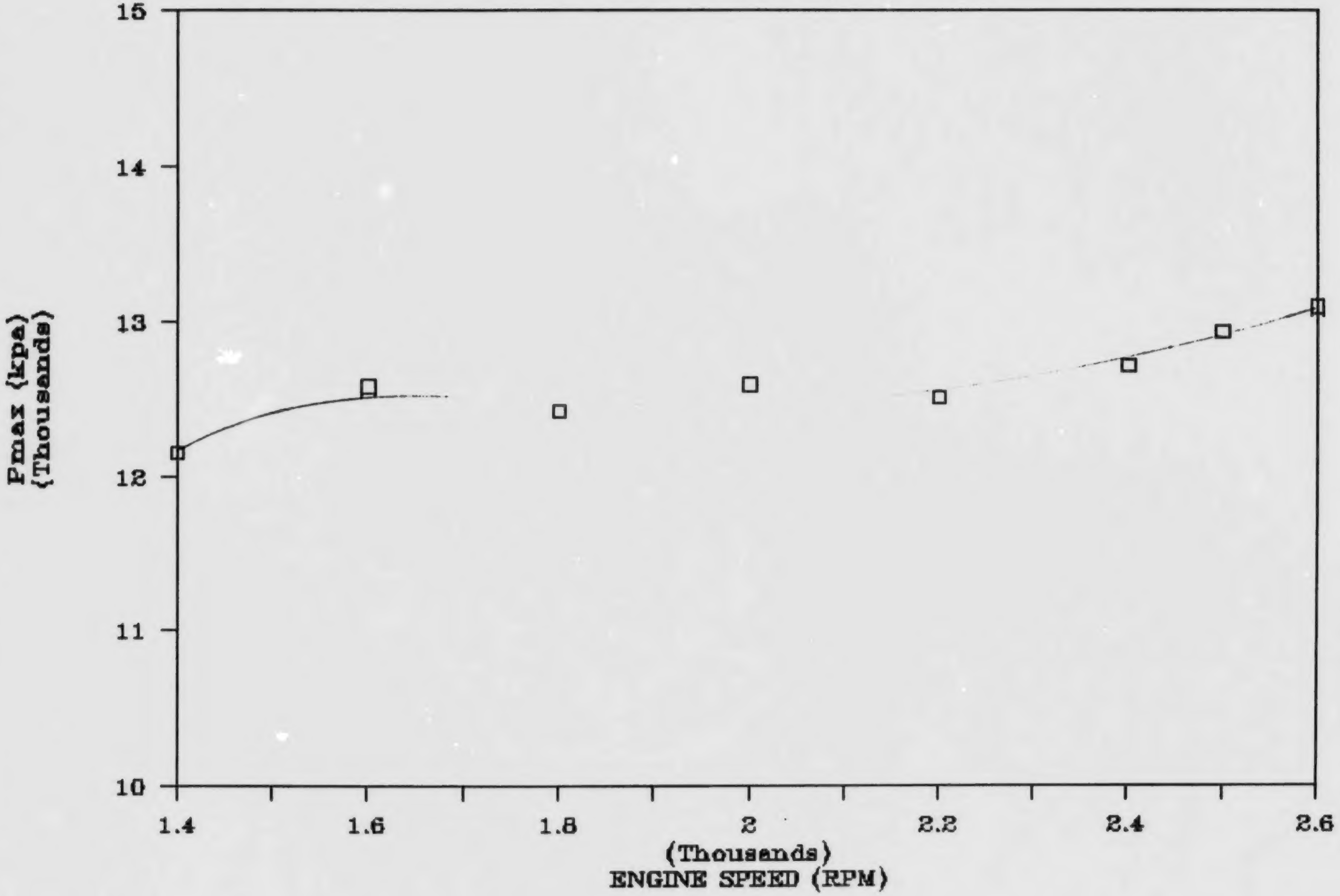
#2 DIESEL + 15% MEOH



Pmax vs. RPM

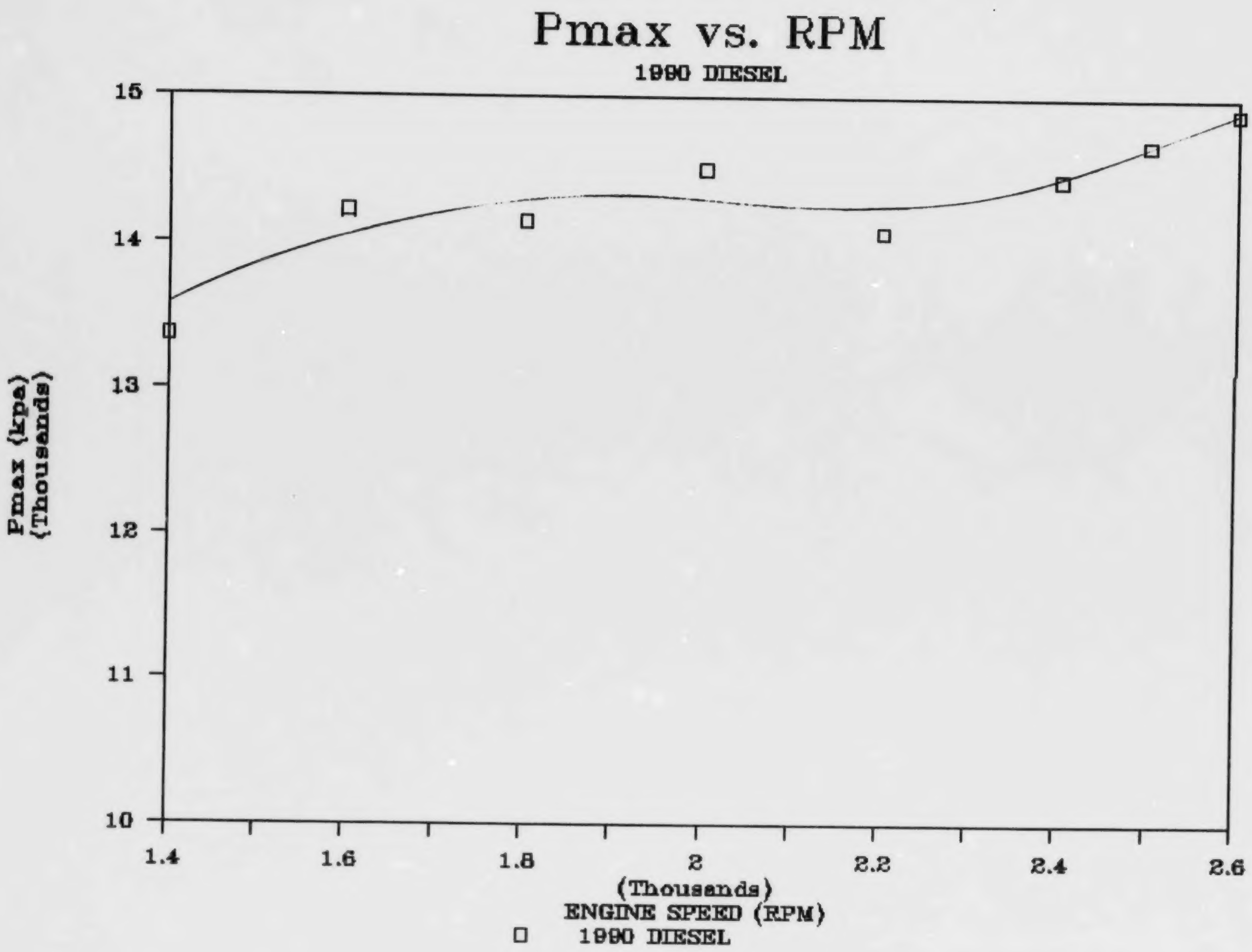
2 DIESEL + 15% MEOH + DII





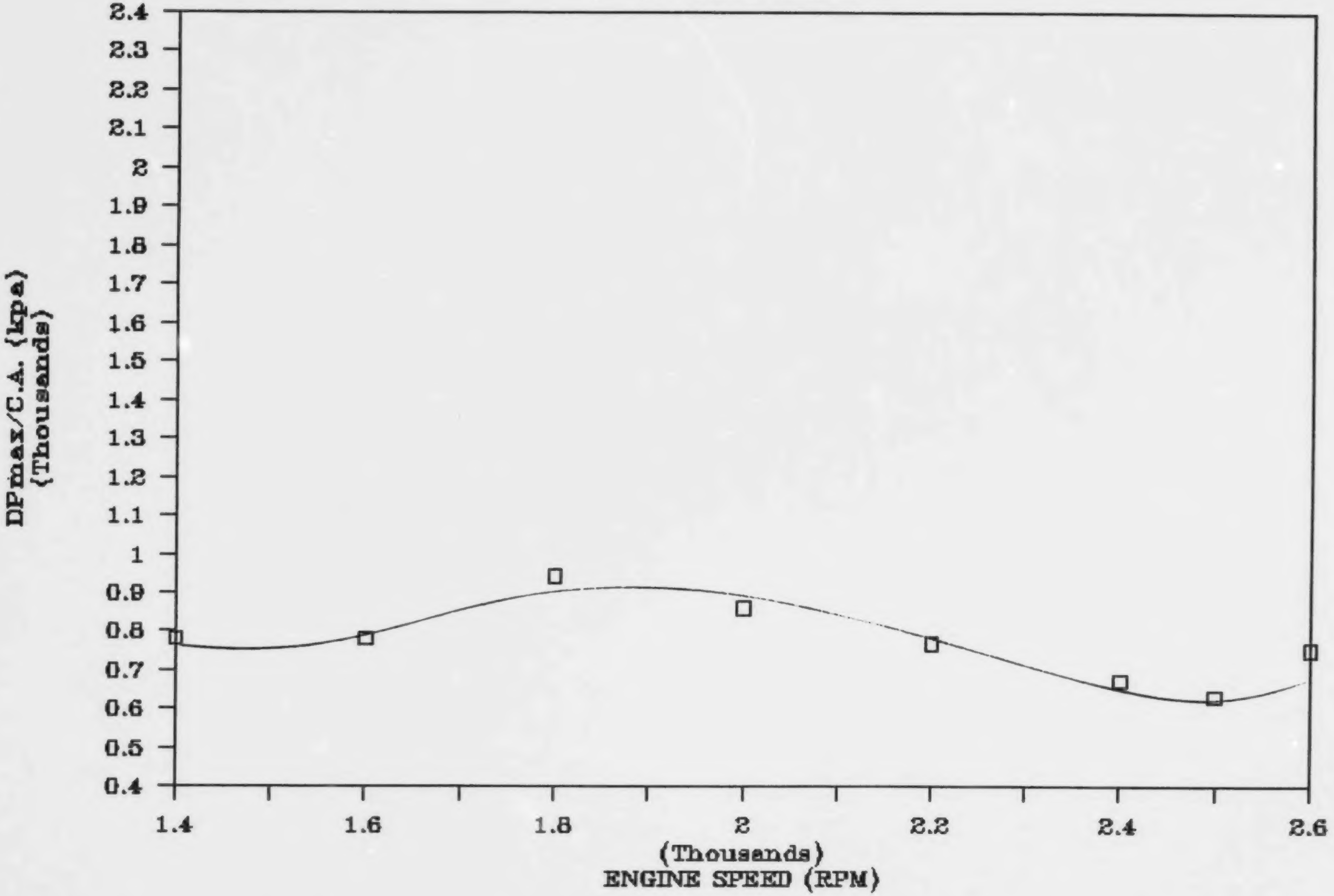
Pmax vs. RPM

2 DIESEL + 20% MEOH + DII


Pmax vs. RPM
1990 DIESEL
Pmax (kpa)
(Thousands)
15
14
13
12
11
10
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)
□ 1990 DIESEL

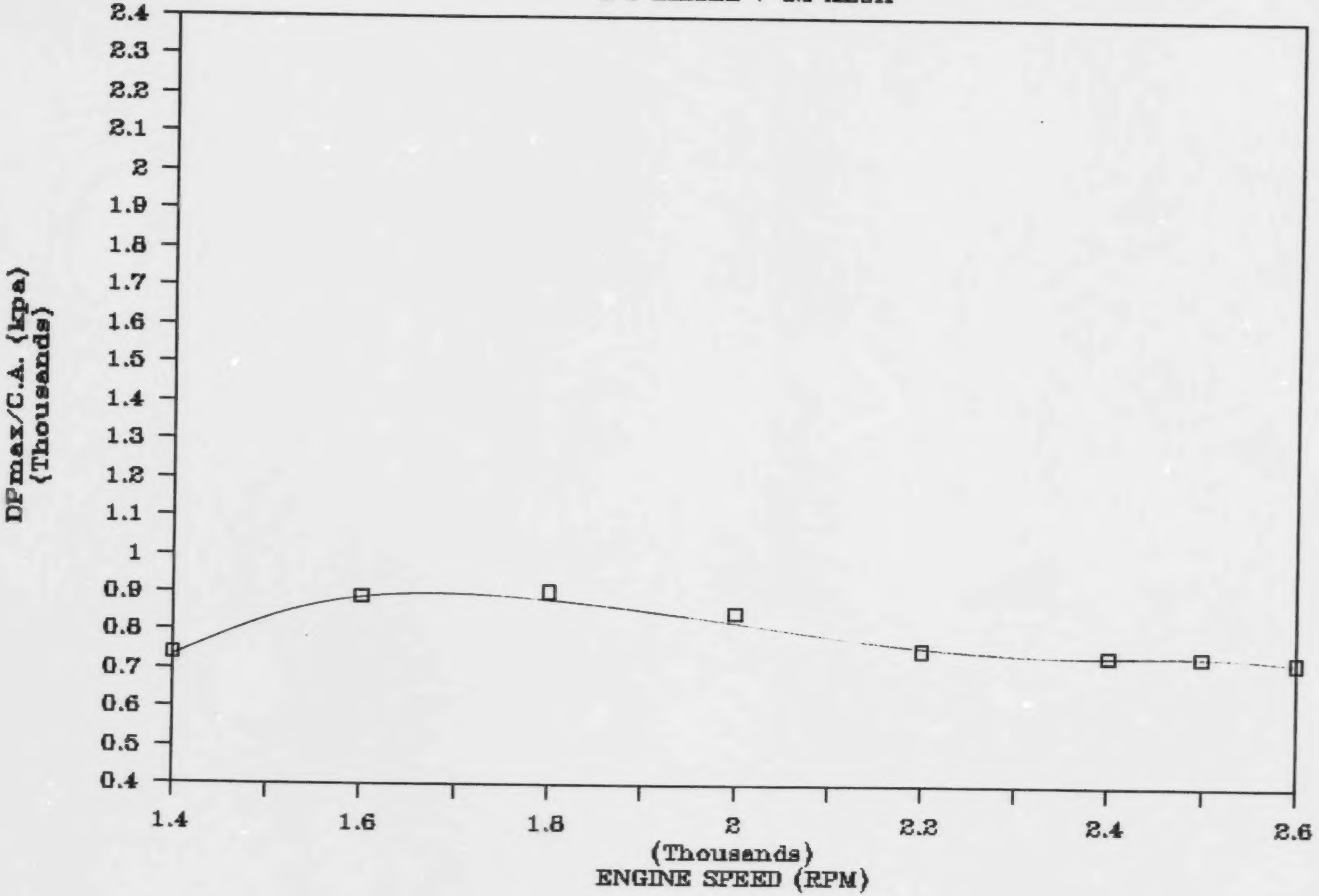
DPmax/C.A. vs. RPM

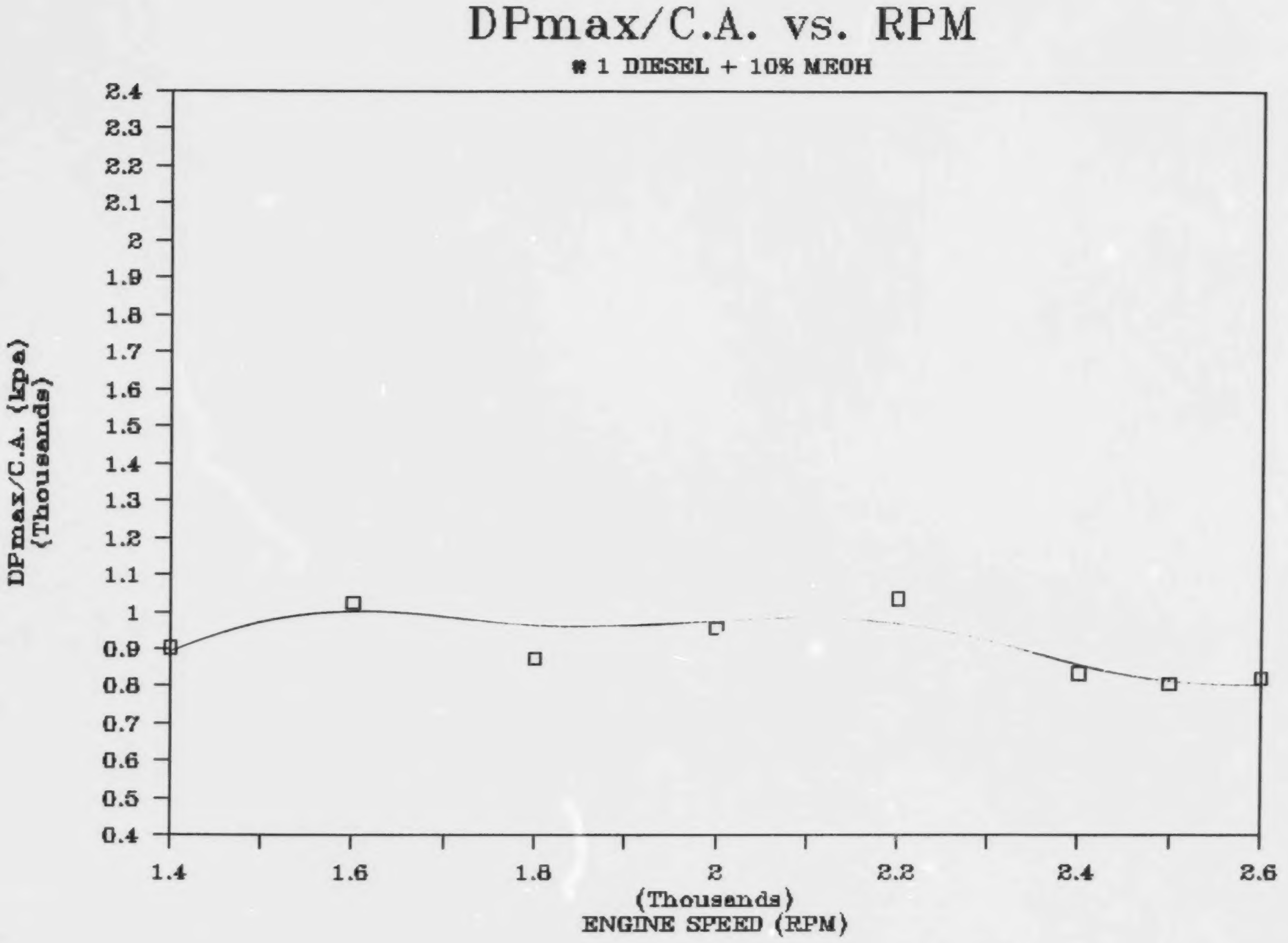
1 NEAT DIESEL

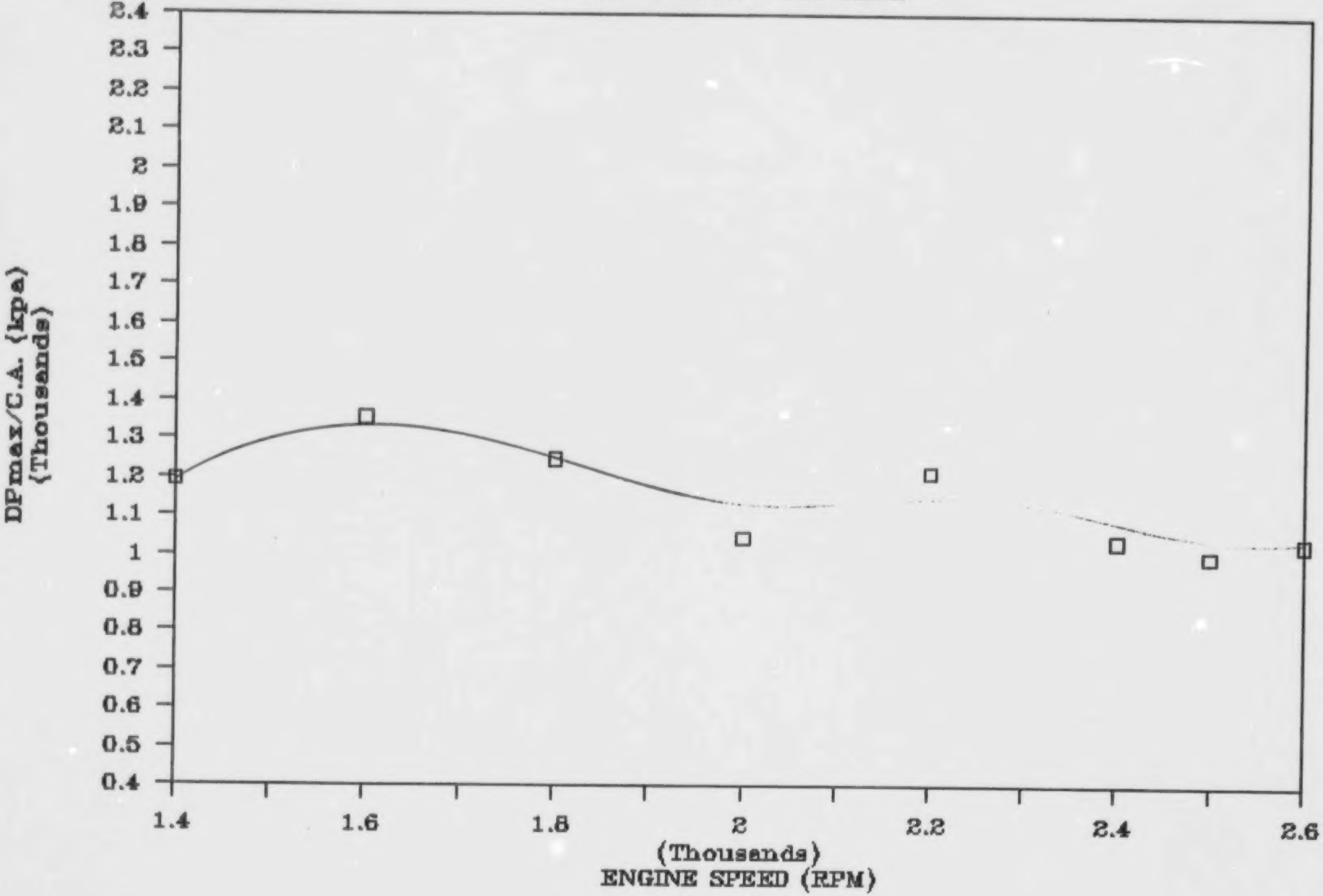


DPmax/C.A. vs. RPM

1 DIESEL + 5% MEOH




DPmax/C.A. vs. RPM
# 1 DIESEL + 10% MEOH
DPmax/C.A. (kpa)
(Thousands)
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

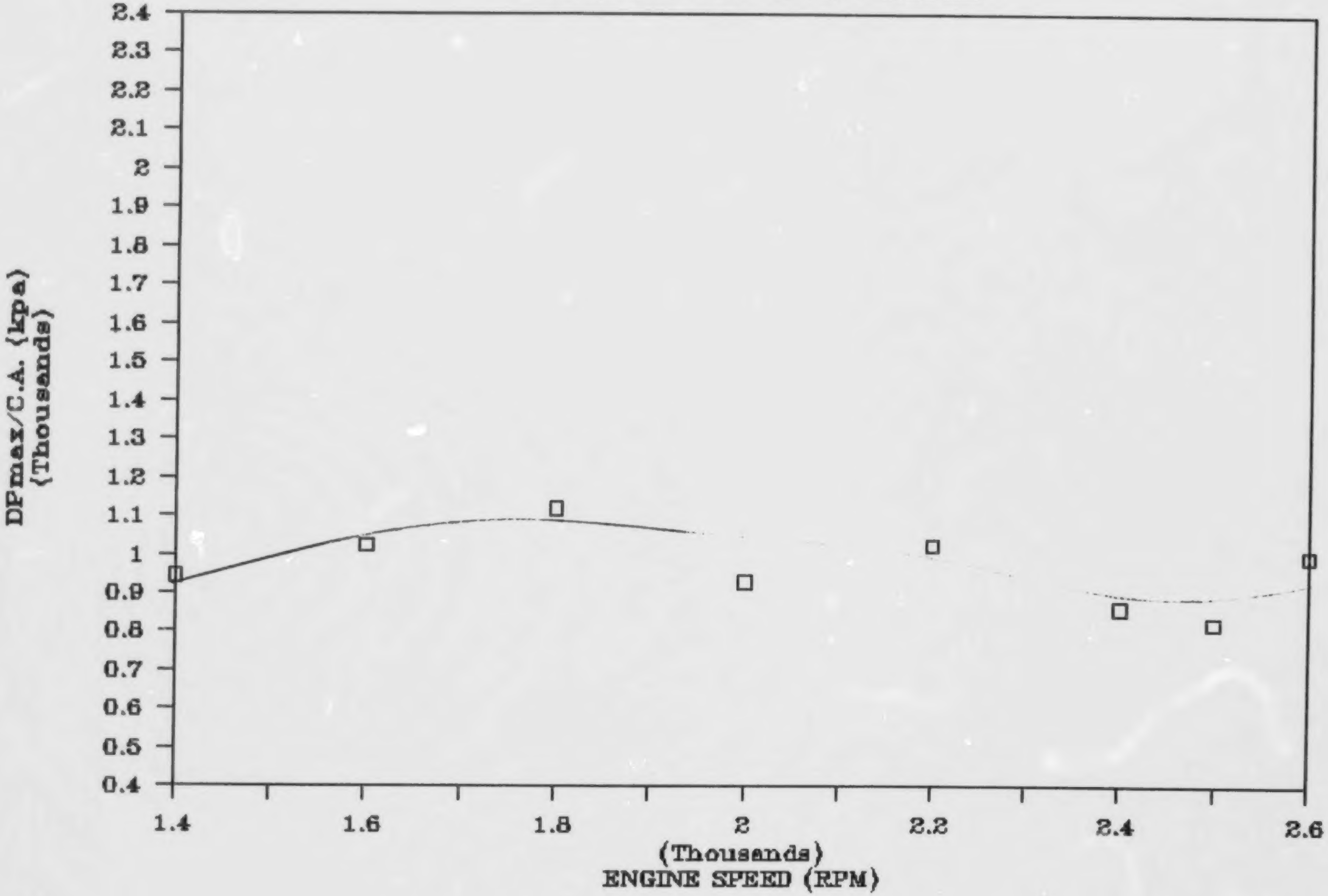


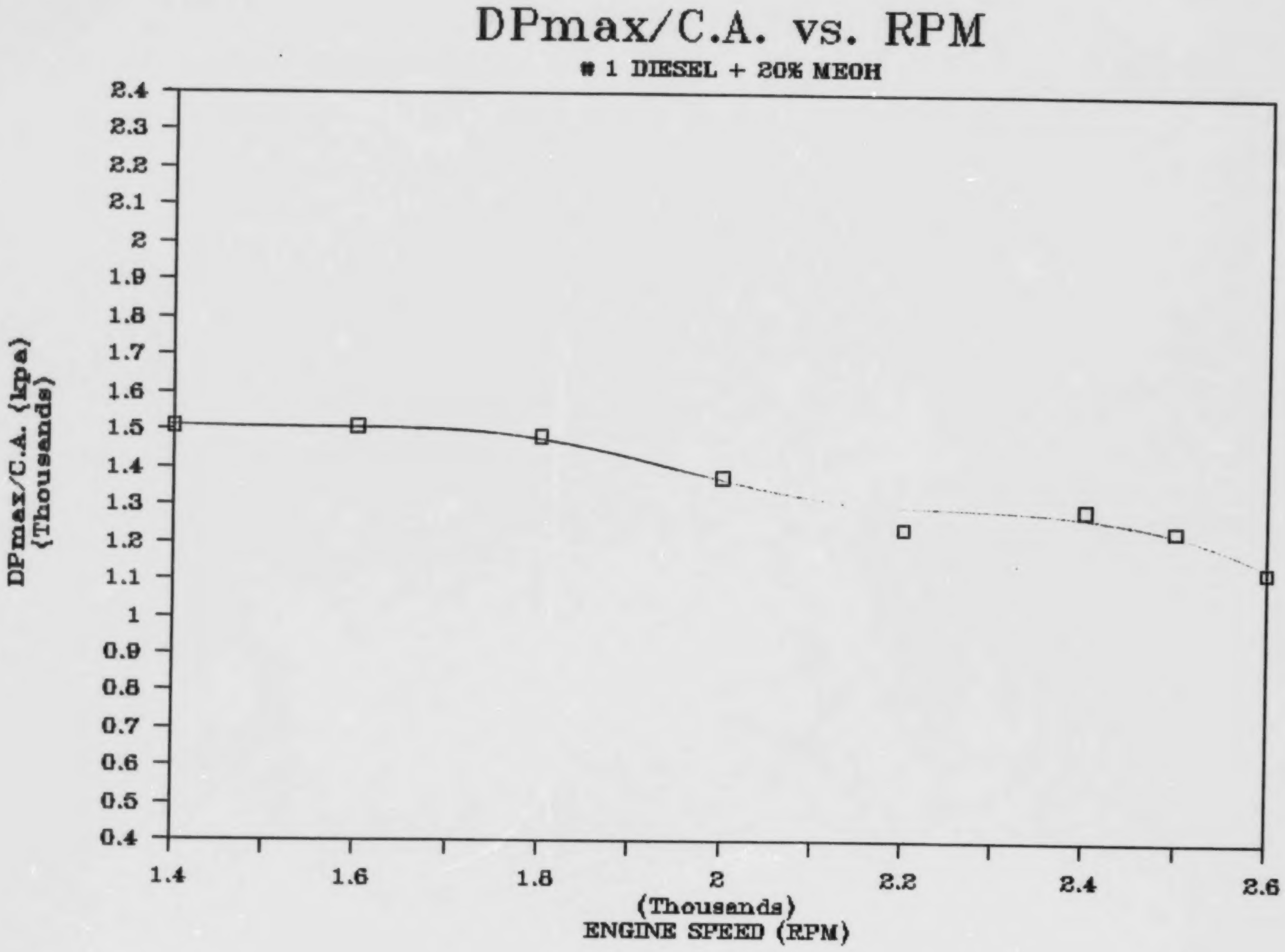
DPmax/C.A. vs. RPM

1 DIESEL + 15% MEOH

DPmax/C.A. vs. RPM

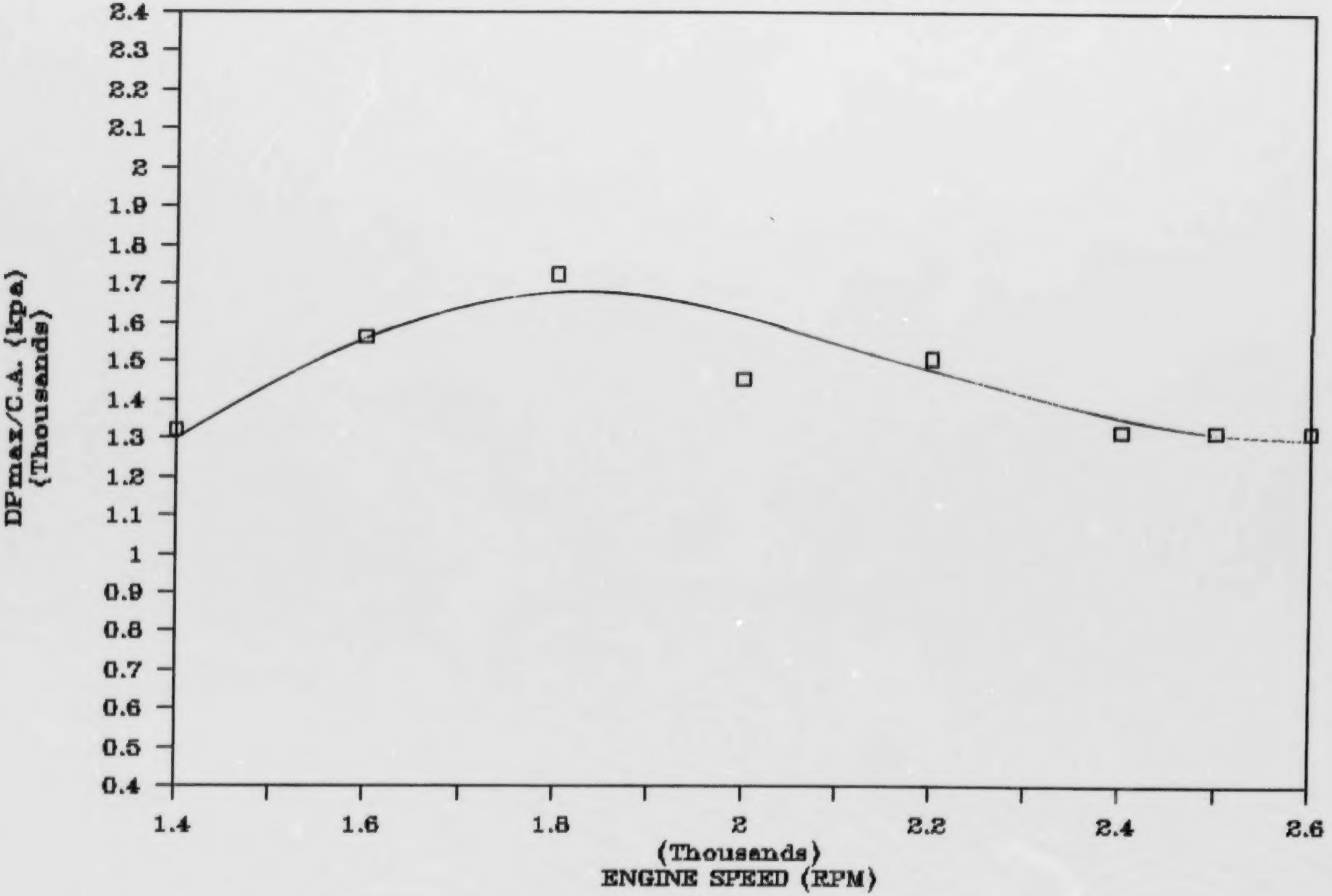
1 DIESEL + 15% MEOH + 0.1% DII




DPmax/C.A. vs. RPM
# 1 DIESEL + 20% MEOH
DPmax/C.A. (kpa)
(Thousands)
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

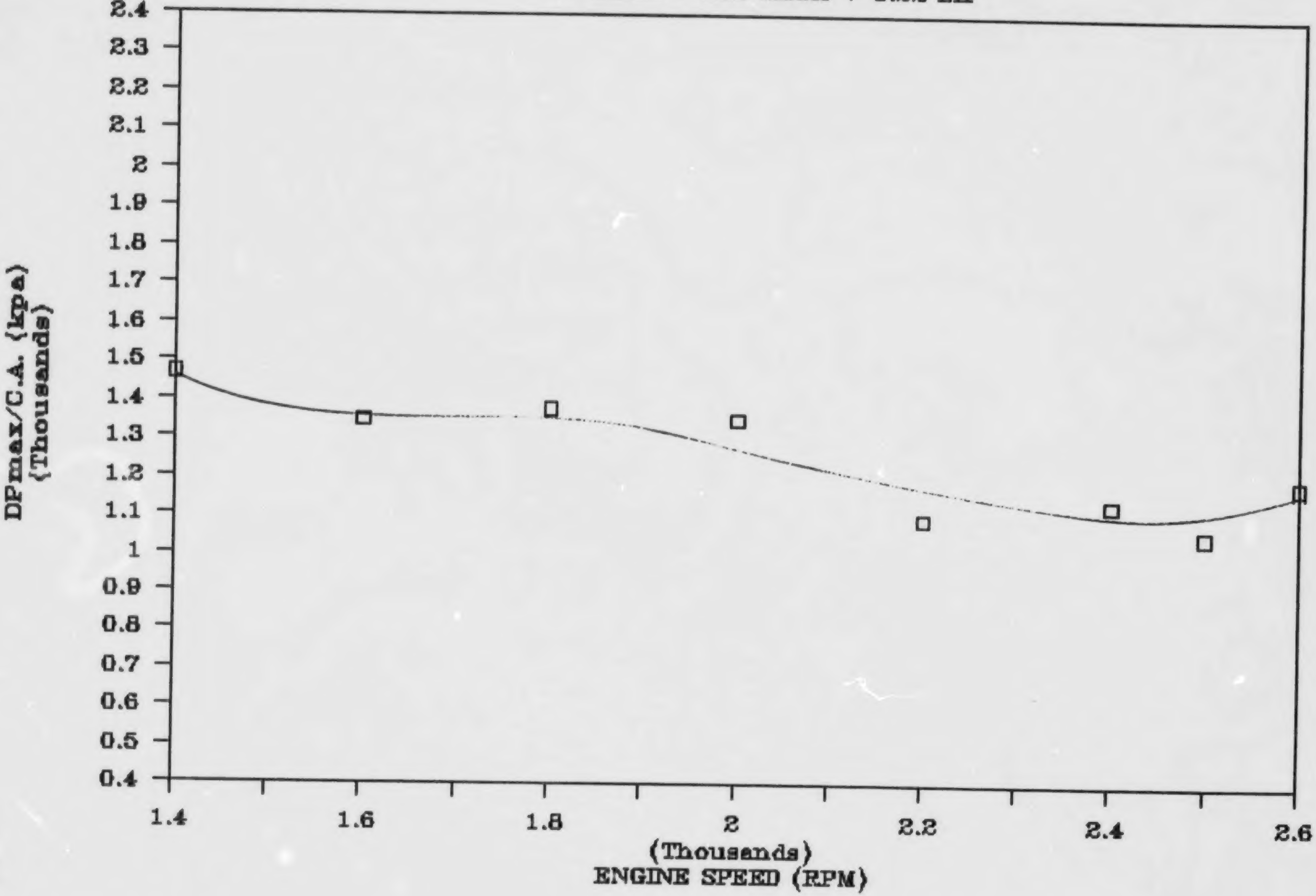
DPmax/C.A. vs. RPM

1 DIESEL + 25% MEOH



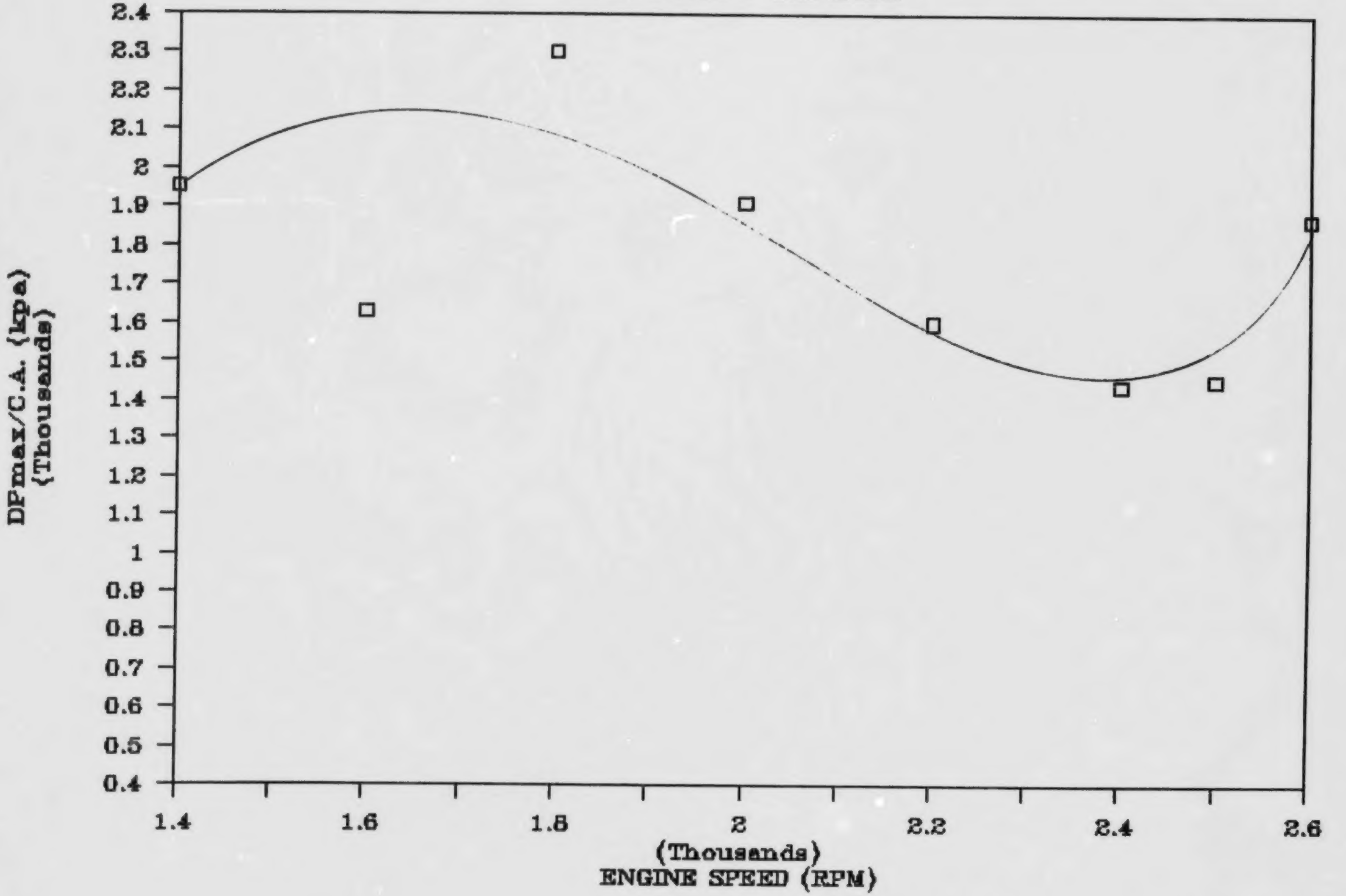
DPmax/C.A. vs. RPM

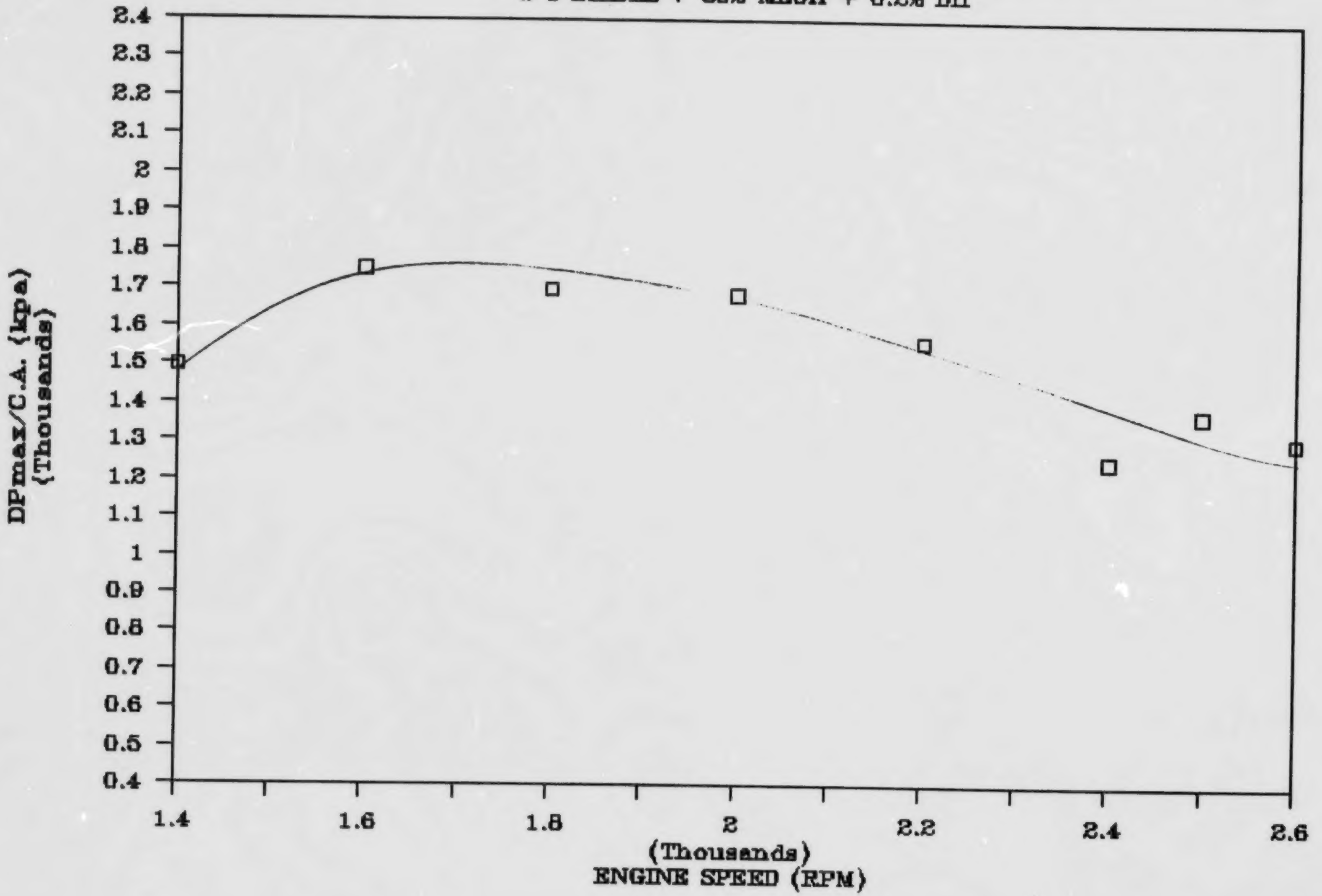
# 1 DIESEL + 25% MEOH + 0.2% DII



DPmax/C.A. vs. RPM

#1 DIESEL + 30% MEOH



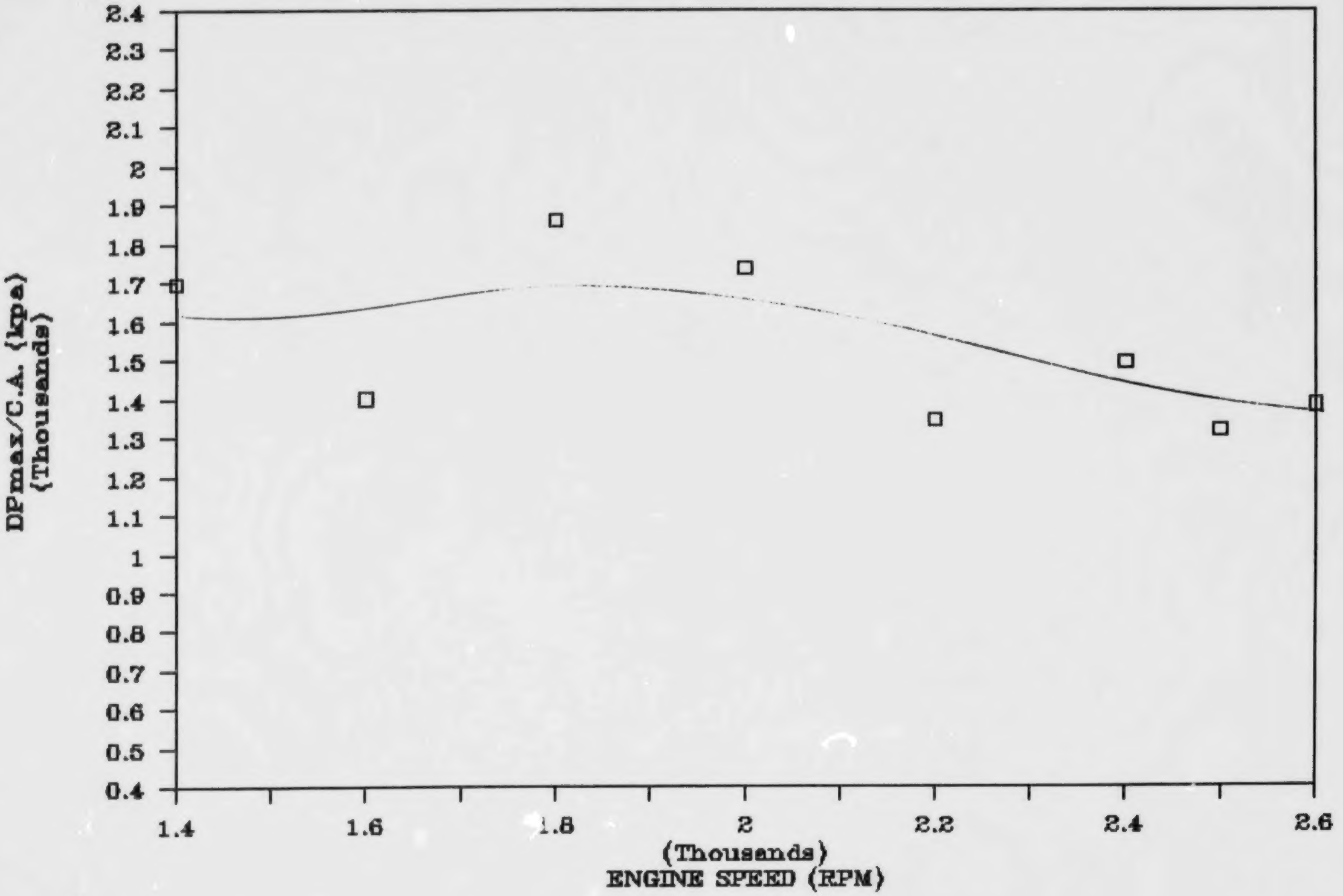


DPmax/C.A. vs. RPM

1 DIESEL + 30% MEOH + 0.2% DII

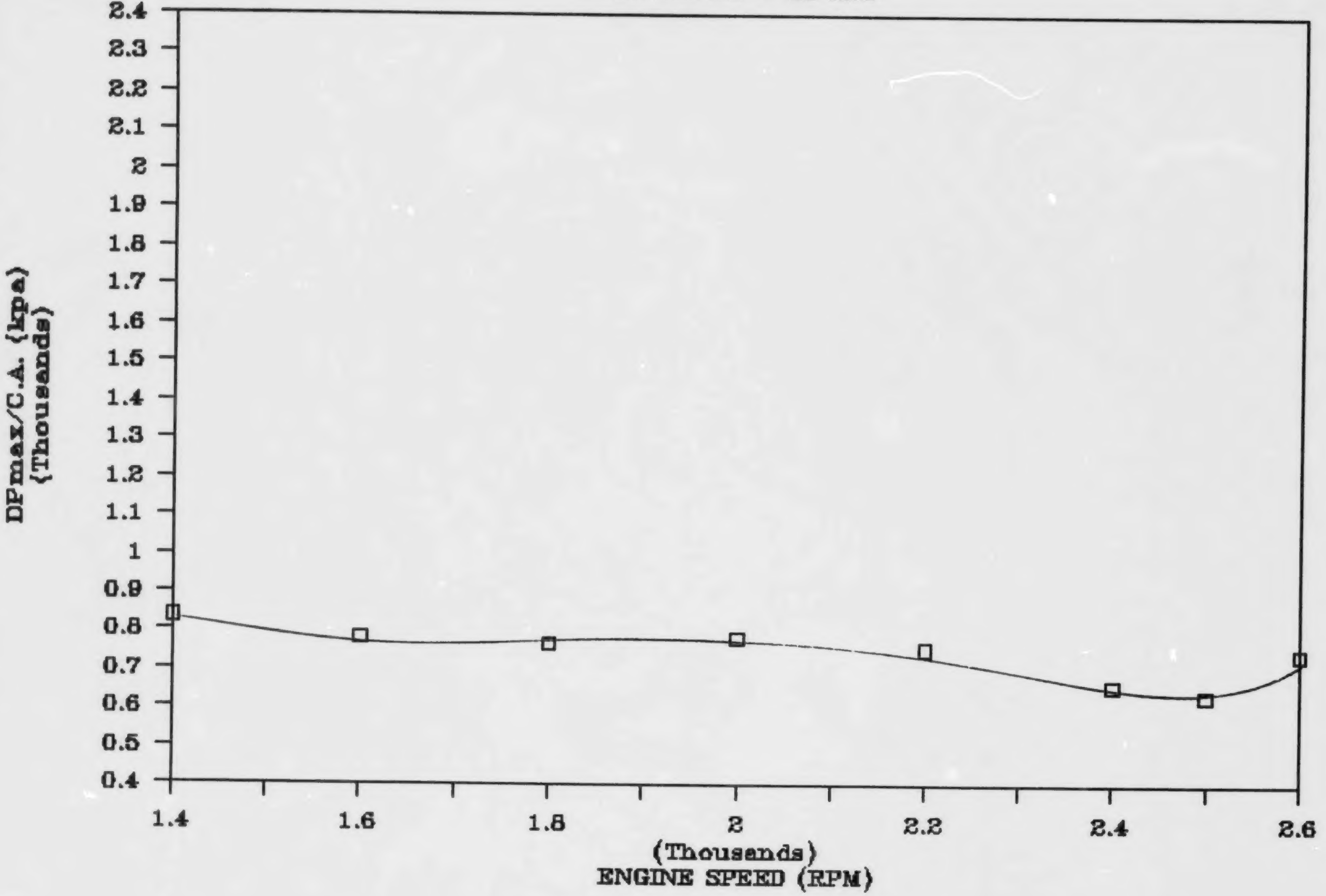
DPmax/C.A. vs. RPM

1 DIESEL + 30% MEOH + 0.4% DII



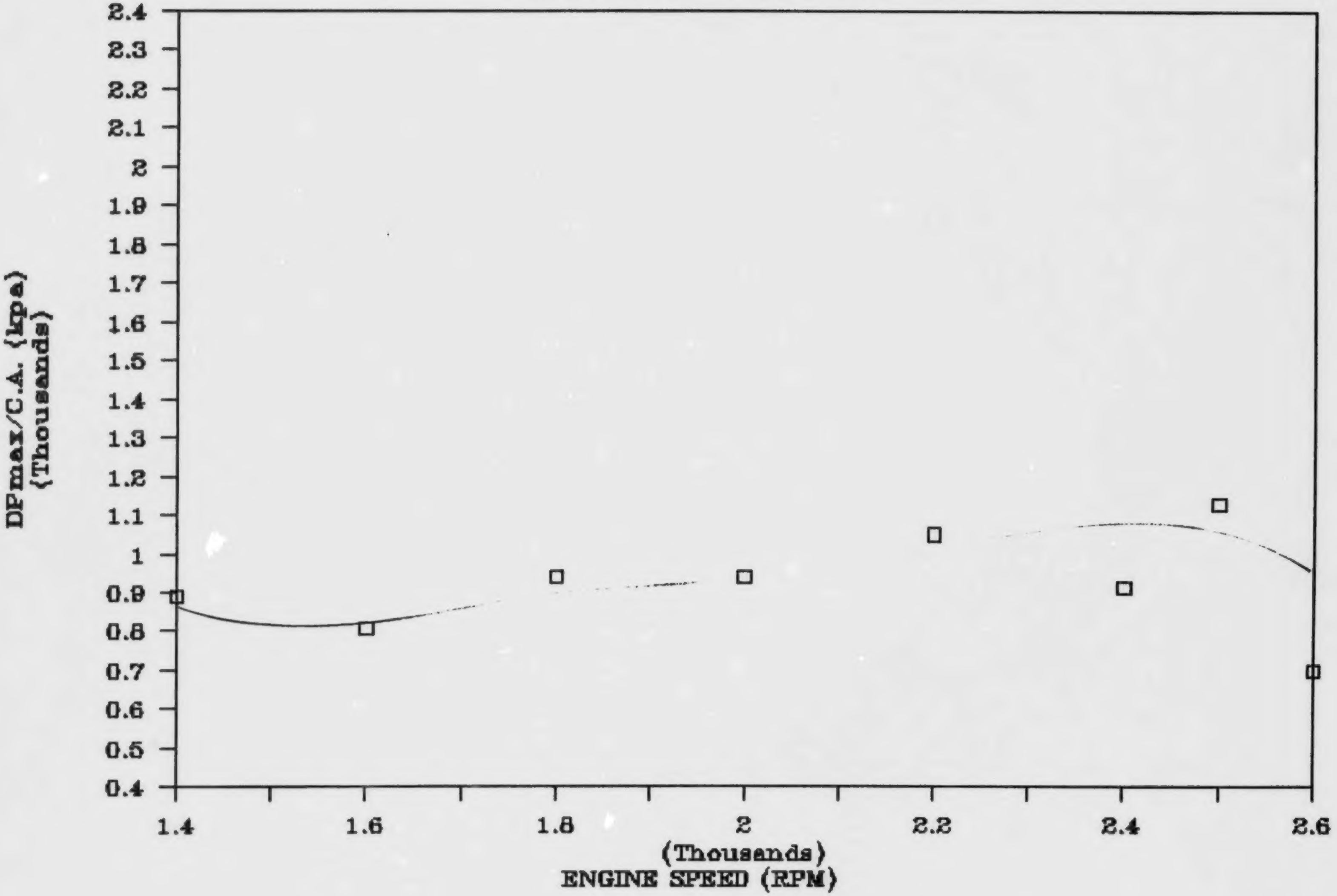
DPmax/C.A. vs. RPM

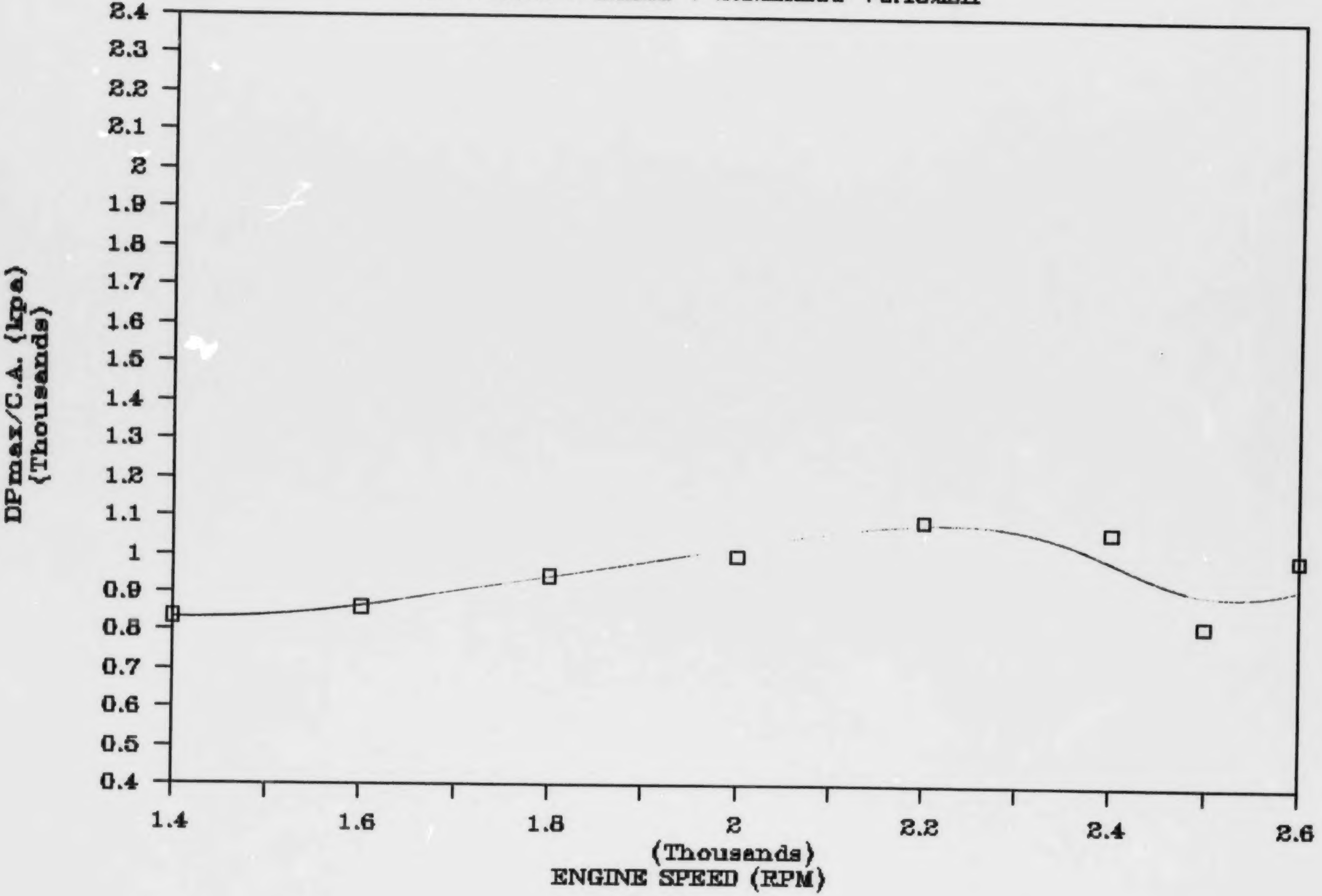
#1 DIESEL + 5% H20



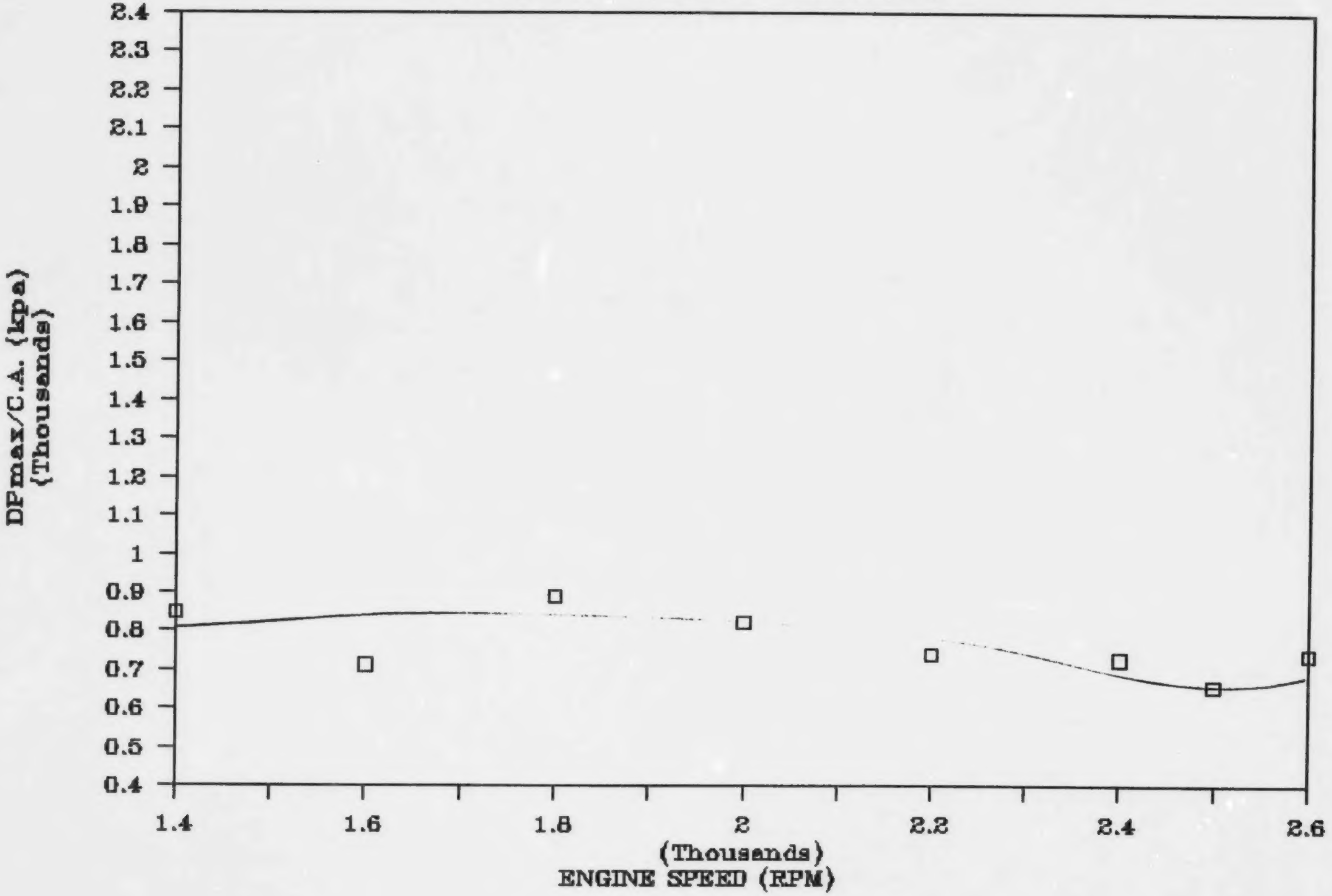
DPmax/C.A. vs. RPM

#1 + 5% H20 + 2.5% DALCO



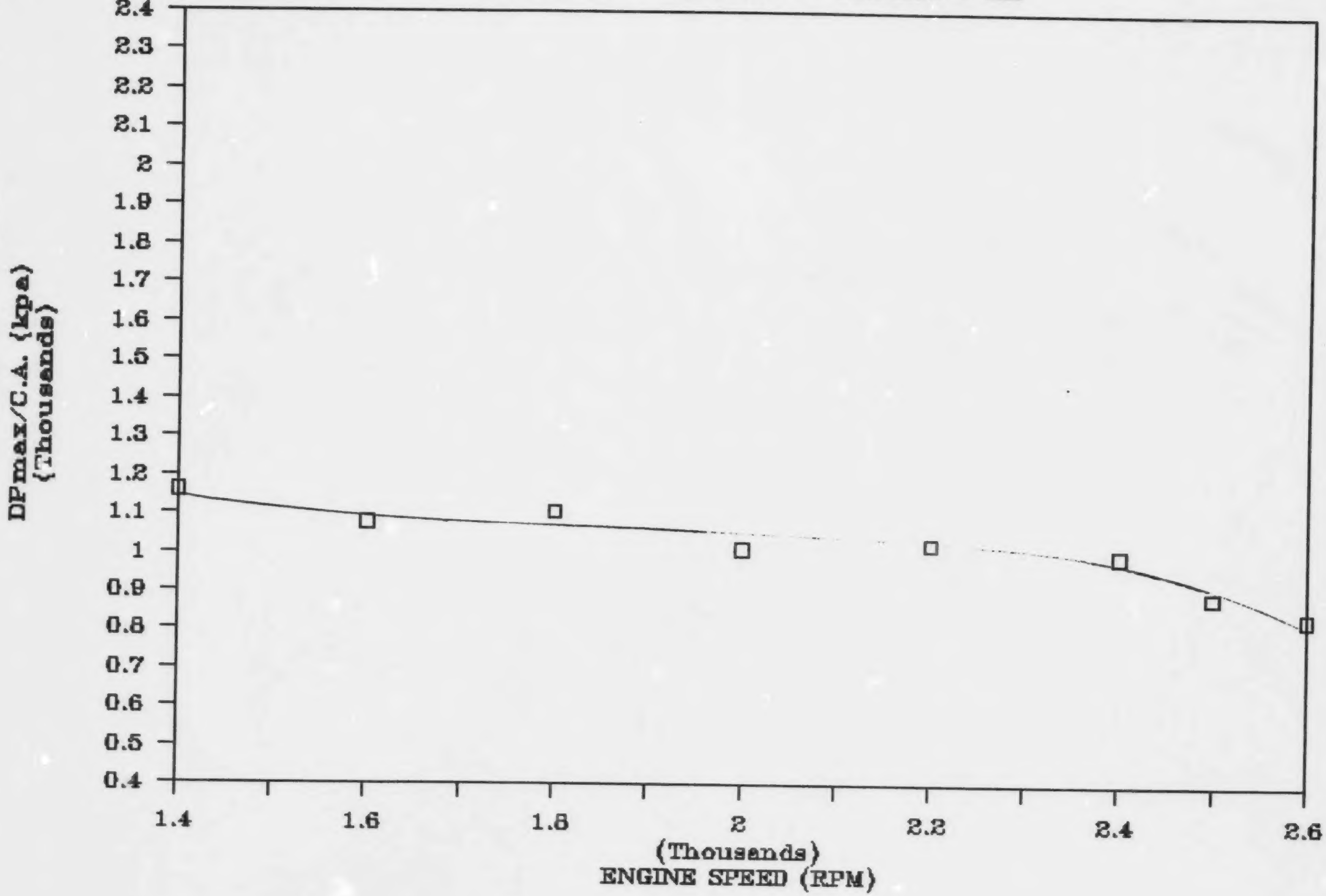

DPmax/C.A. vs. RPM

#1 DIESEL + 5%H20 + 2.5%DALCO +0.15%DII



DPmax/C.A. vs. RPM

#1 DIESEL + 5.5% H2O + 2.75% DALCO

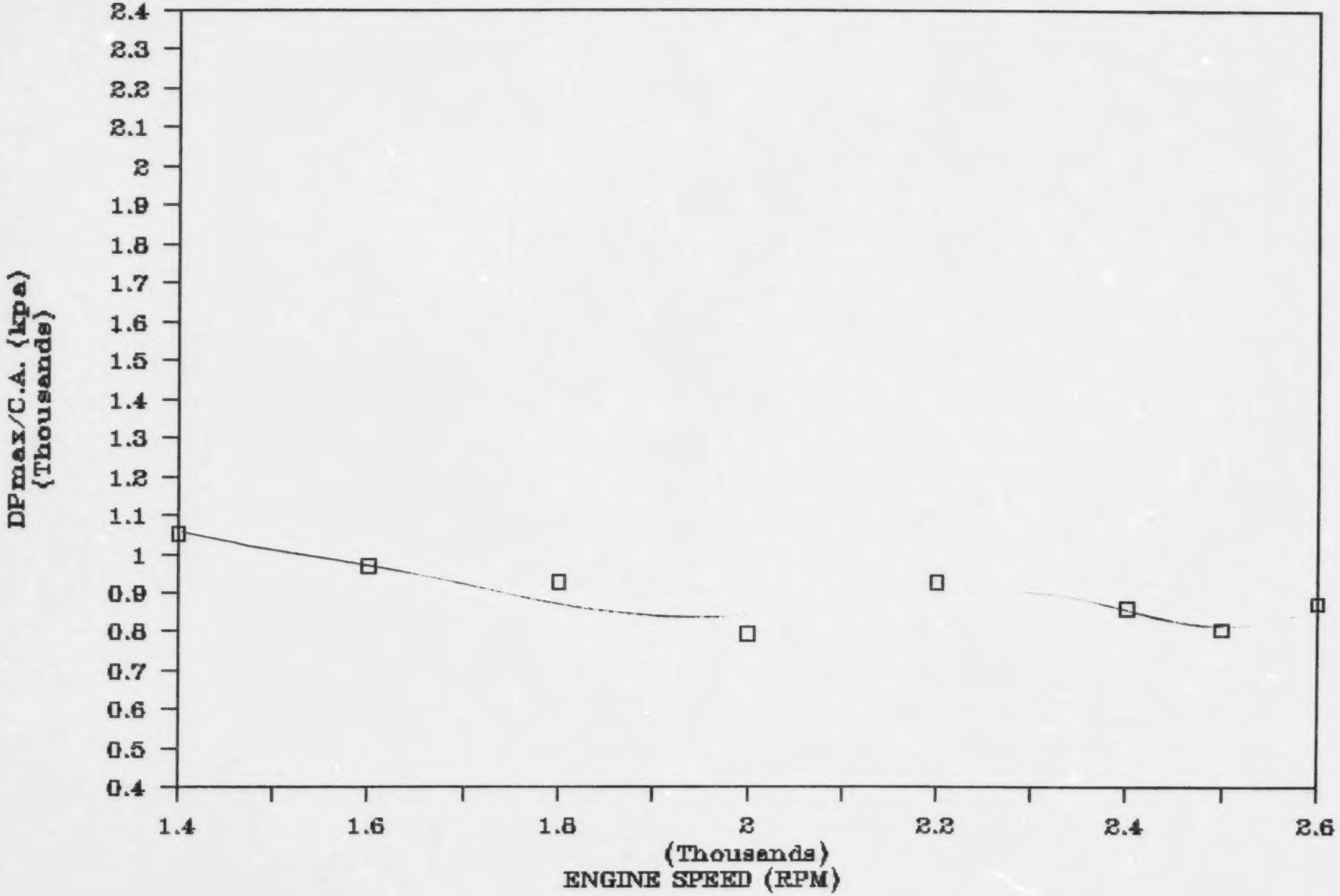


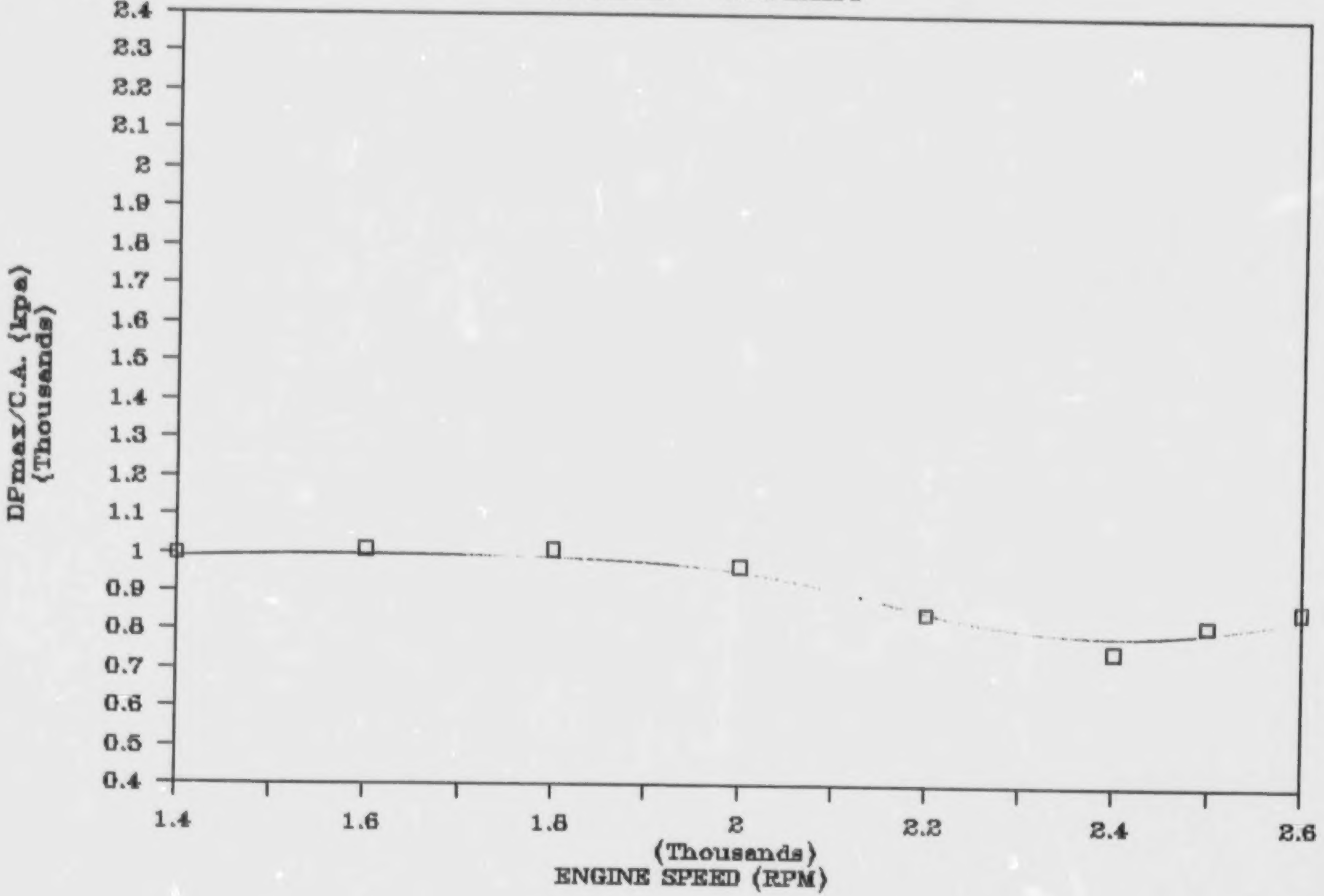
DPmax/C.A. vs. RPM

#1 DIESEL + 15% MEOH + .15% H20 + DII

DPmax/C.A. vs. RPM

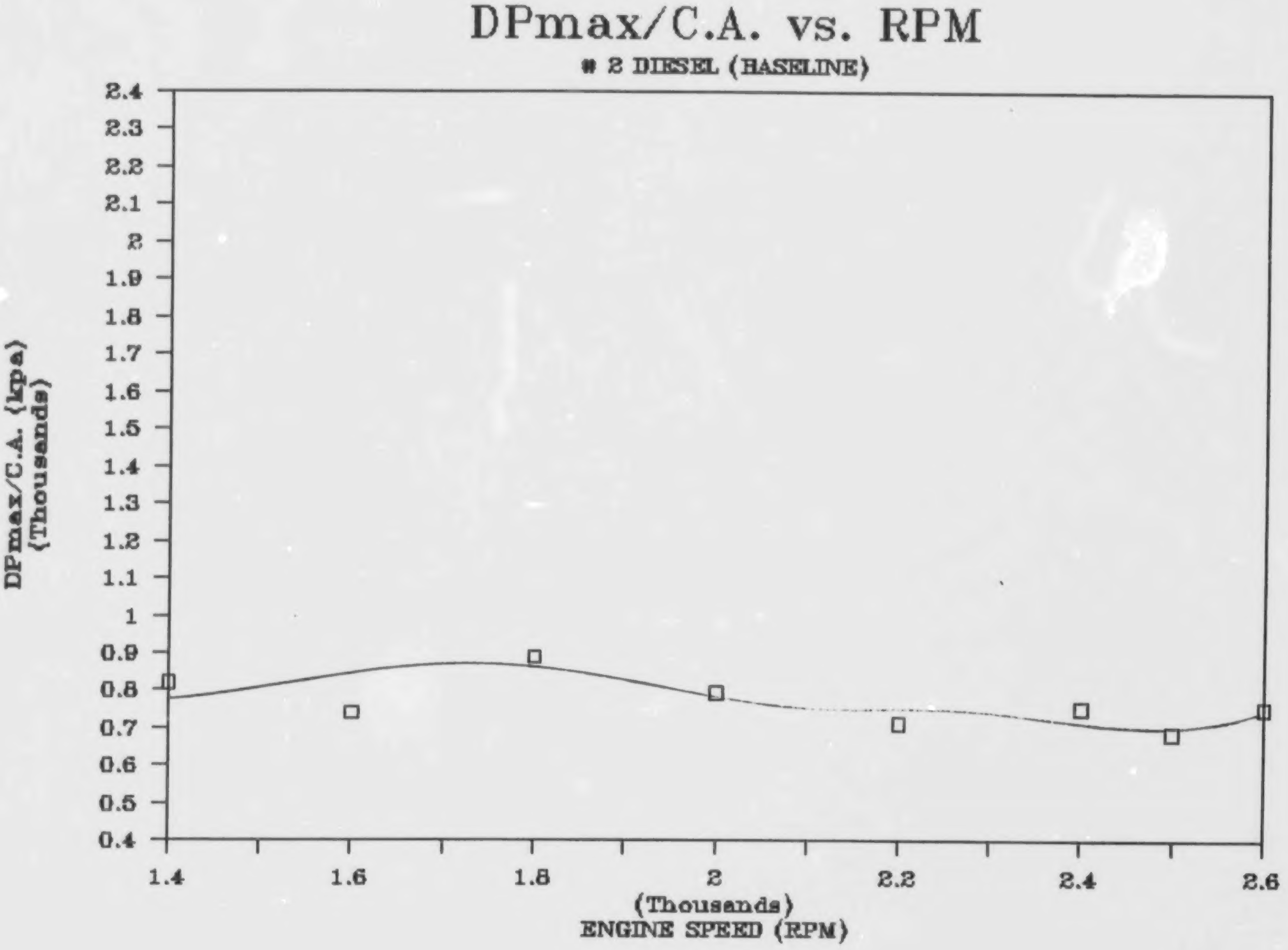
#1 + 7.5%MEOH +7.5%H2O +3%DALCO +.2%DII





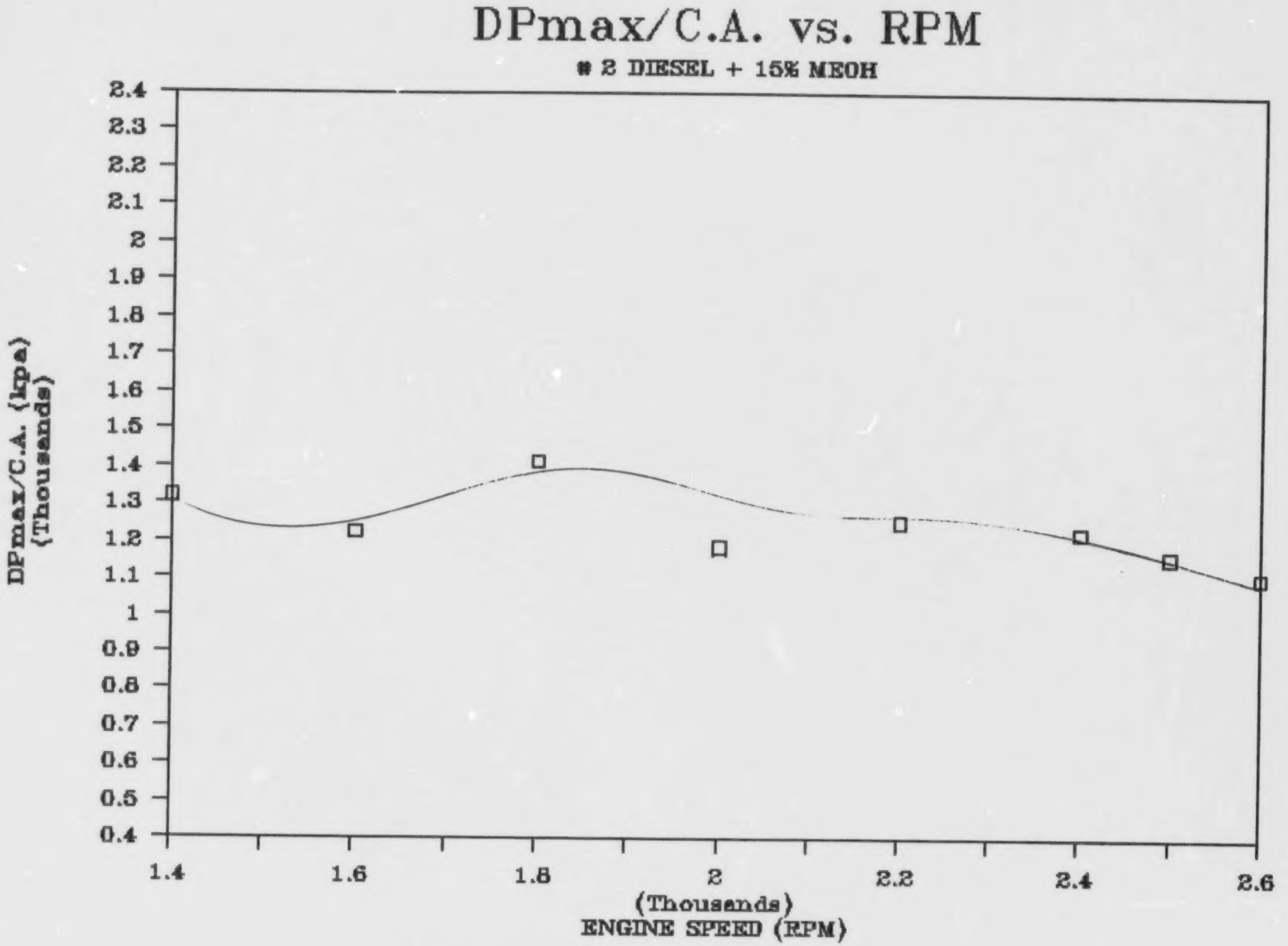
DPmax/C.A. vs. RPM

#1 DIESEL + 2.5% DALCO



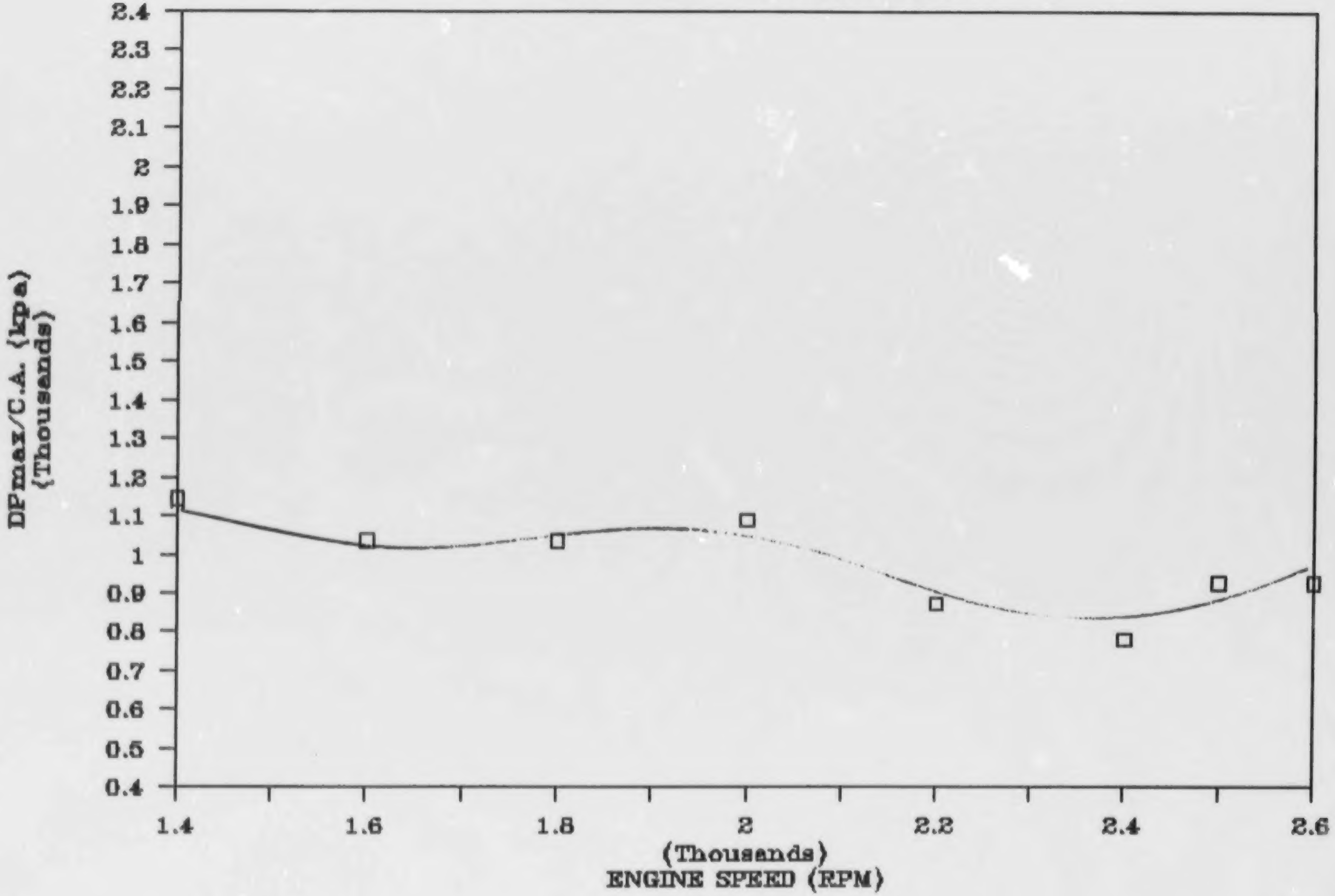
DPmax/C.A. vs. RPM

2 DIESEL (BASELINE)


DPmax/C.A. vs. RPM
# 2 DIESEL + 15% MEOH
DPmax/C.A. (kpa)
(Thousands)
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)

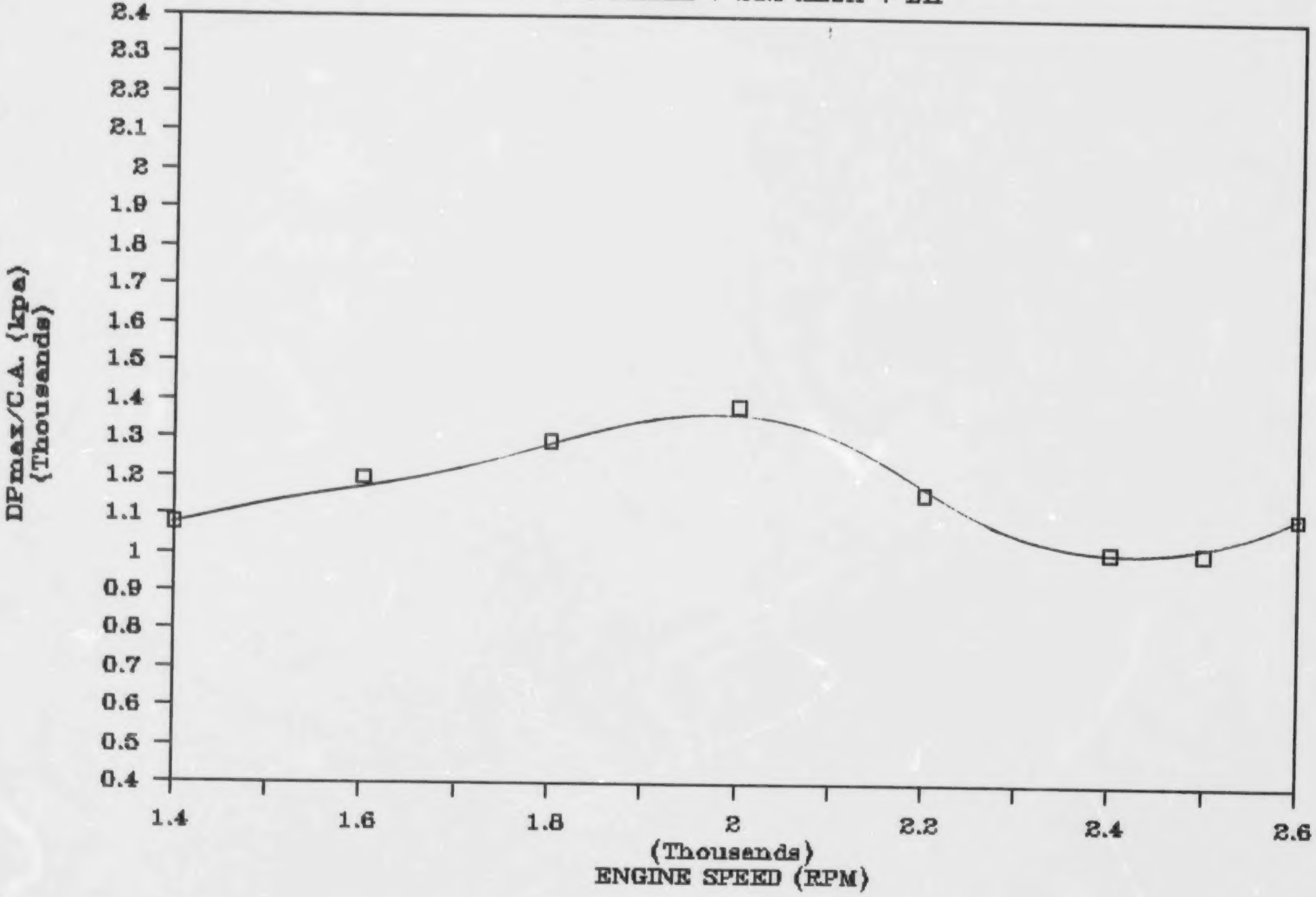
DPmax/C.A. vs. RPM

2 DIESEL + 15% MEOH + DII



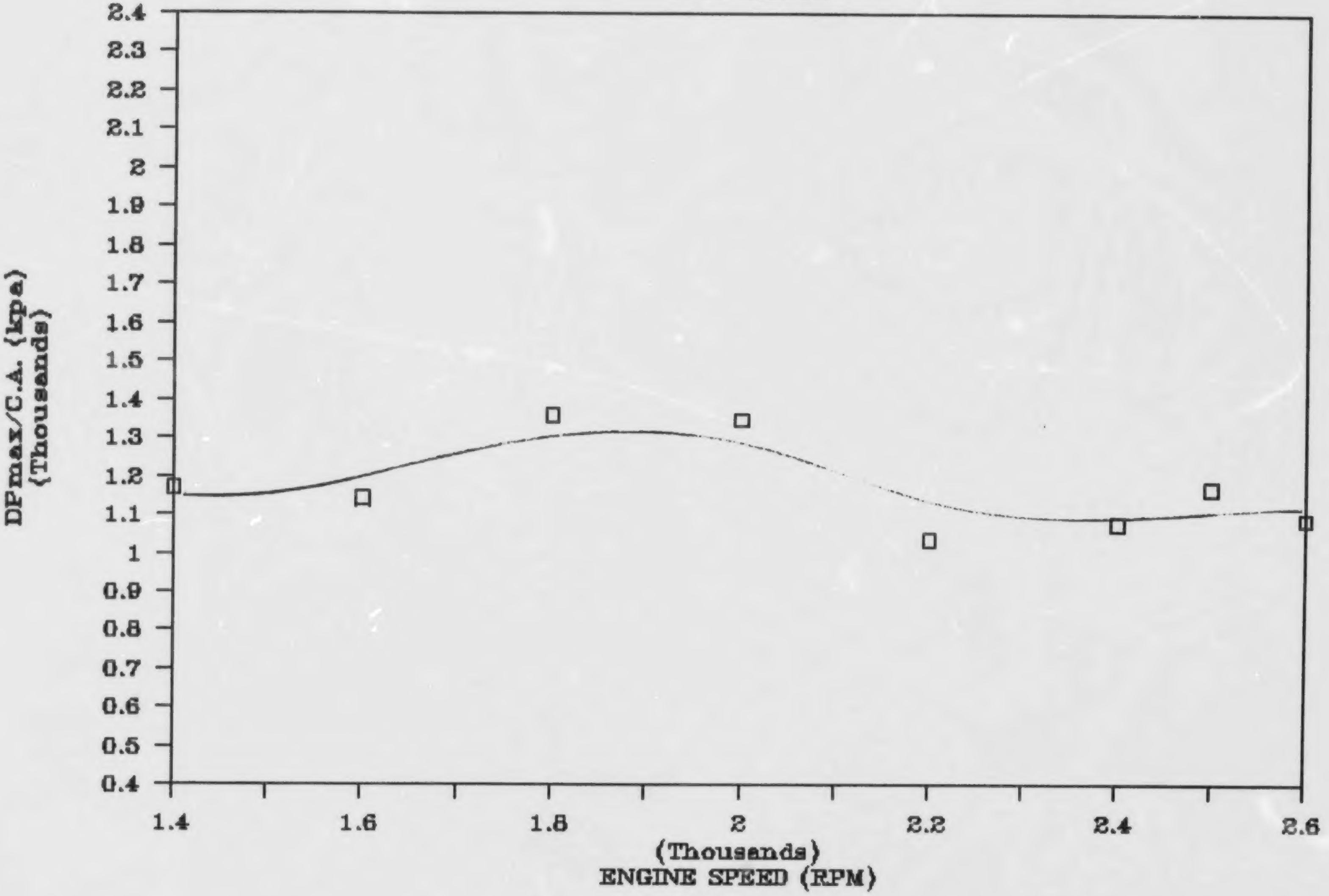
DPmax/C.A. vs. RPM

# 2 DIESEL + 20% MEOH + DII



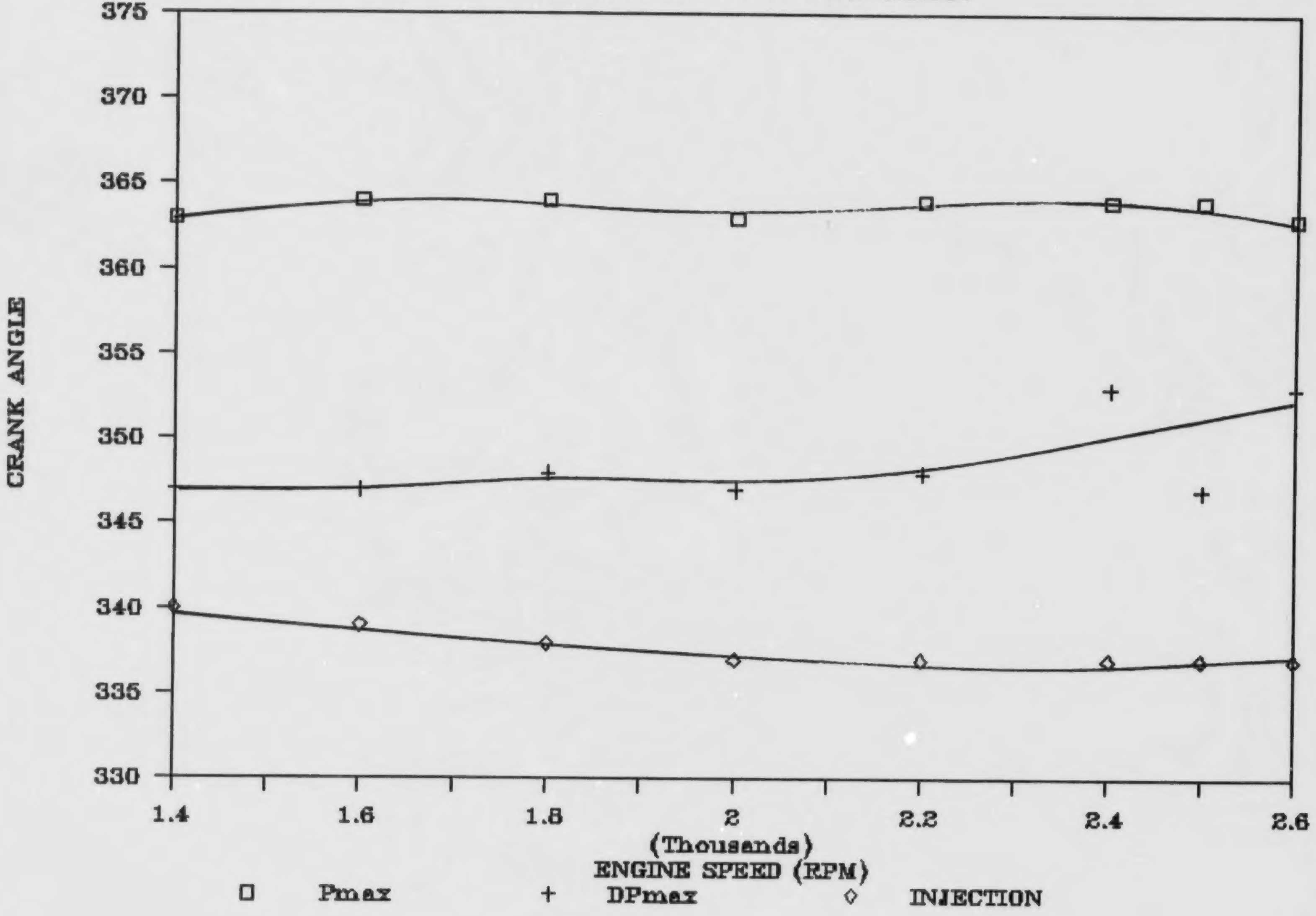
DPmax/C.A. vs. RPM

1990 DIESEL



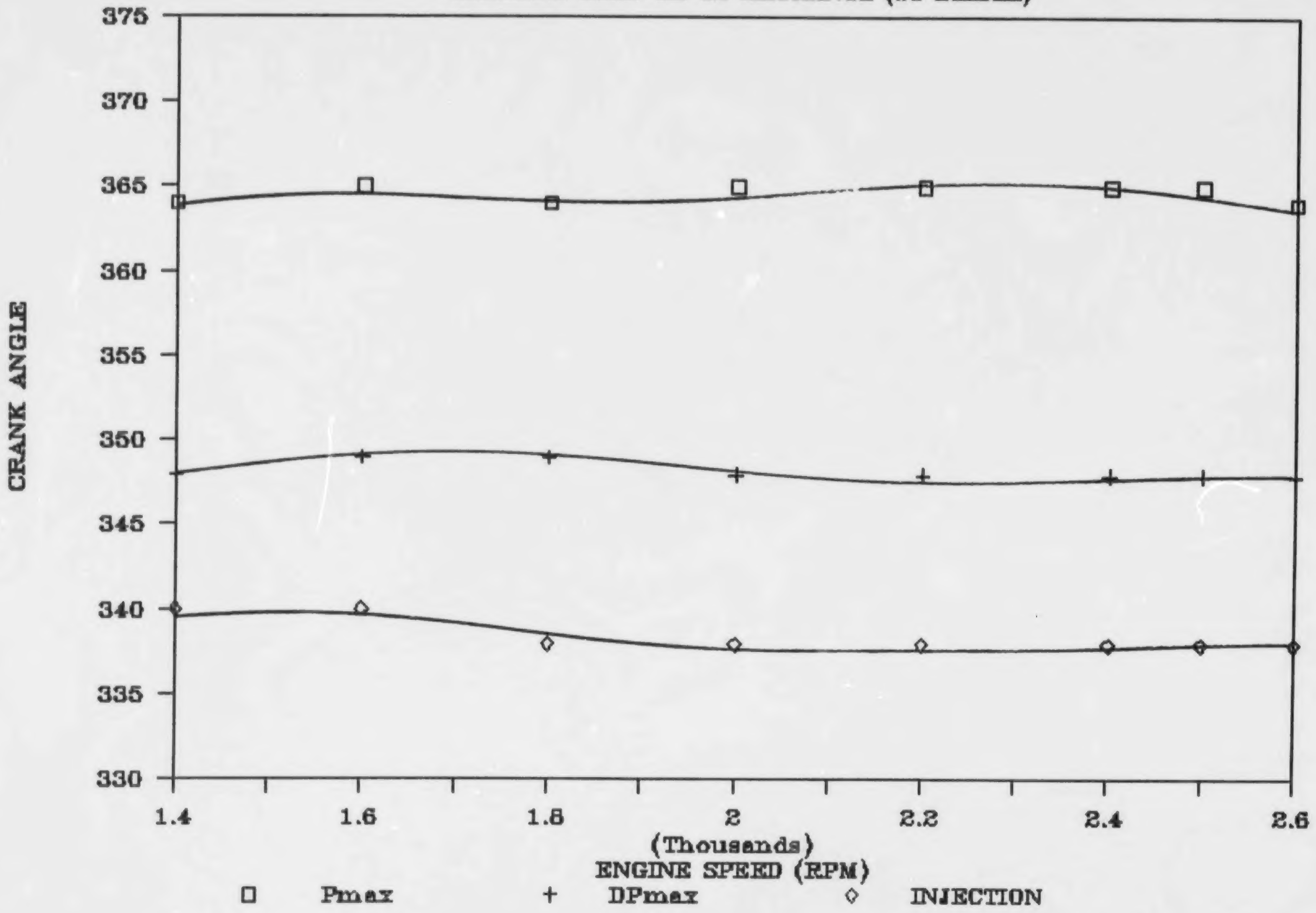
TIMING OF COMBUSTION EVENTS vs. RPM

MAXIMUM LOAD on #1 NEAT DIESEL



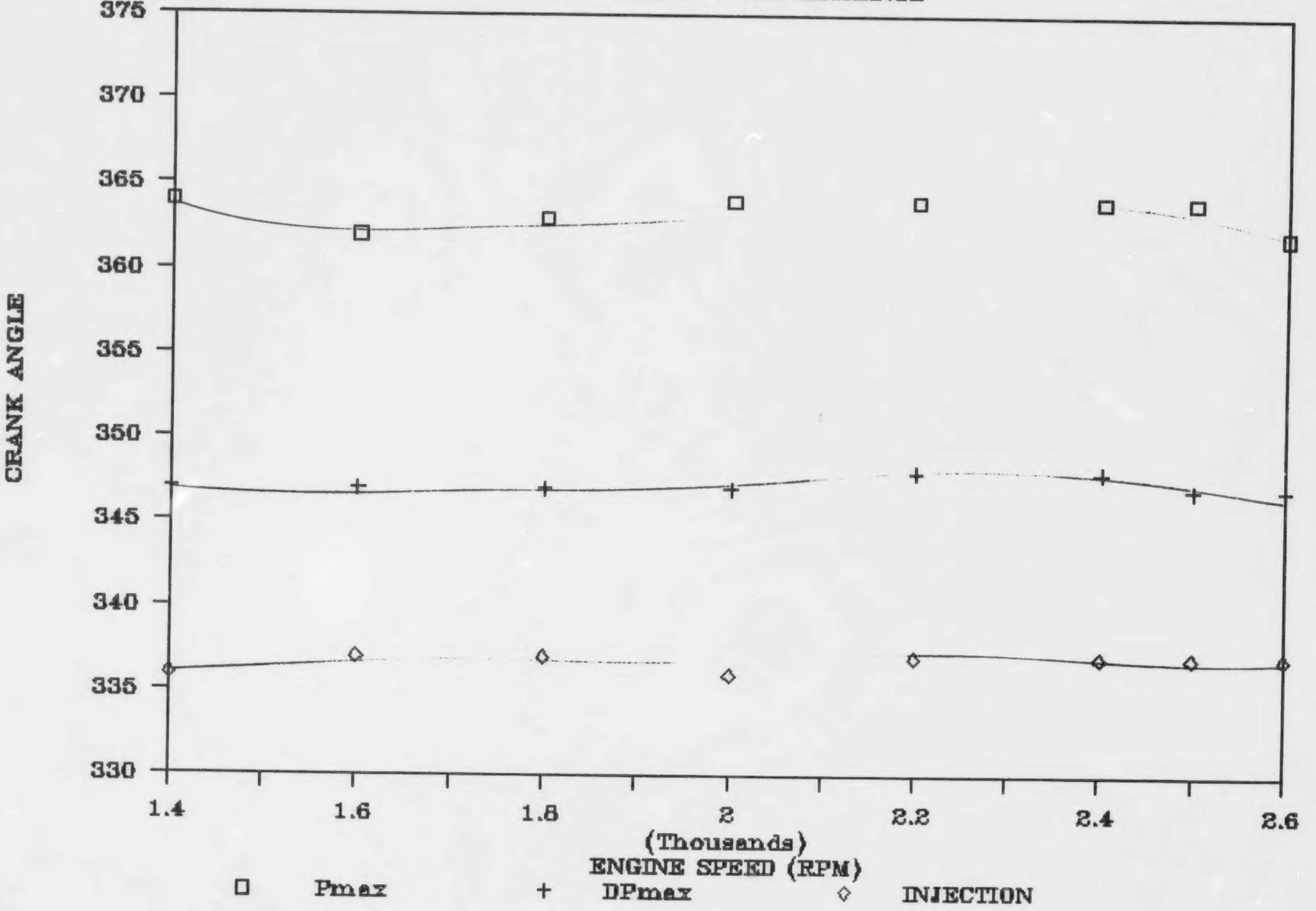
TIMING OF COMBUSTION EVENTS vs. RPM

MAXIMUM LOAD on 5% METHANOL (#1 DIESEL)



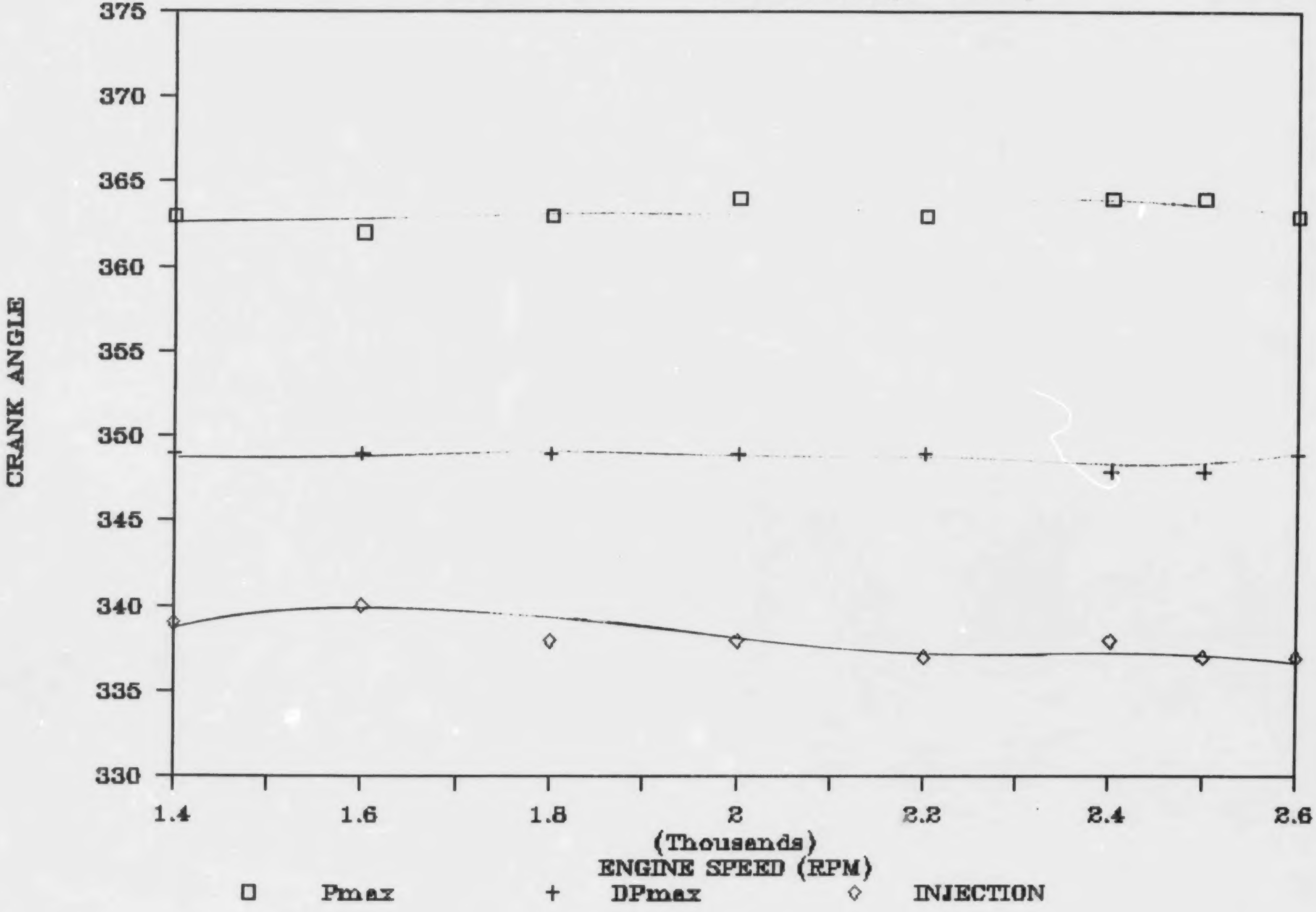
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 10% METHANOL



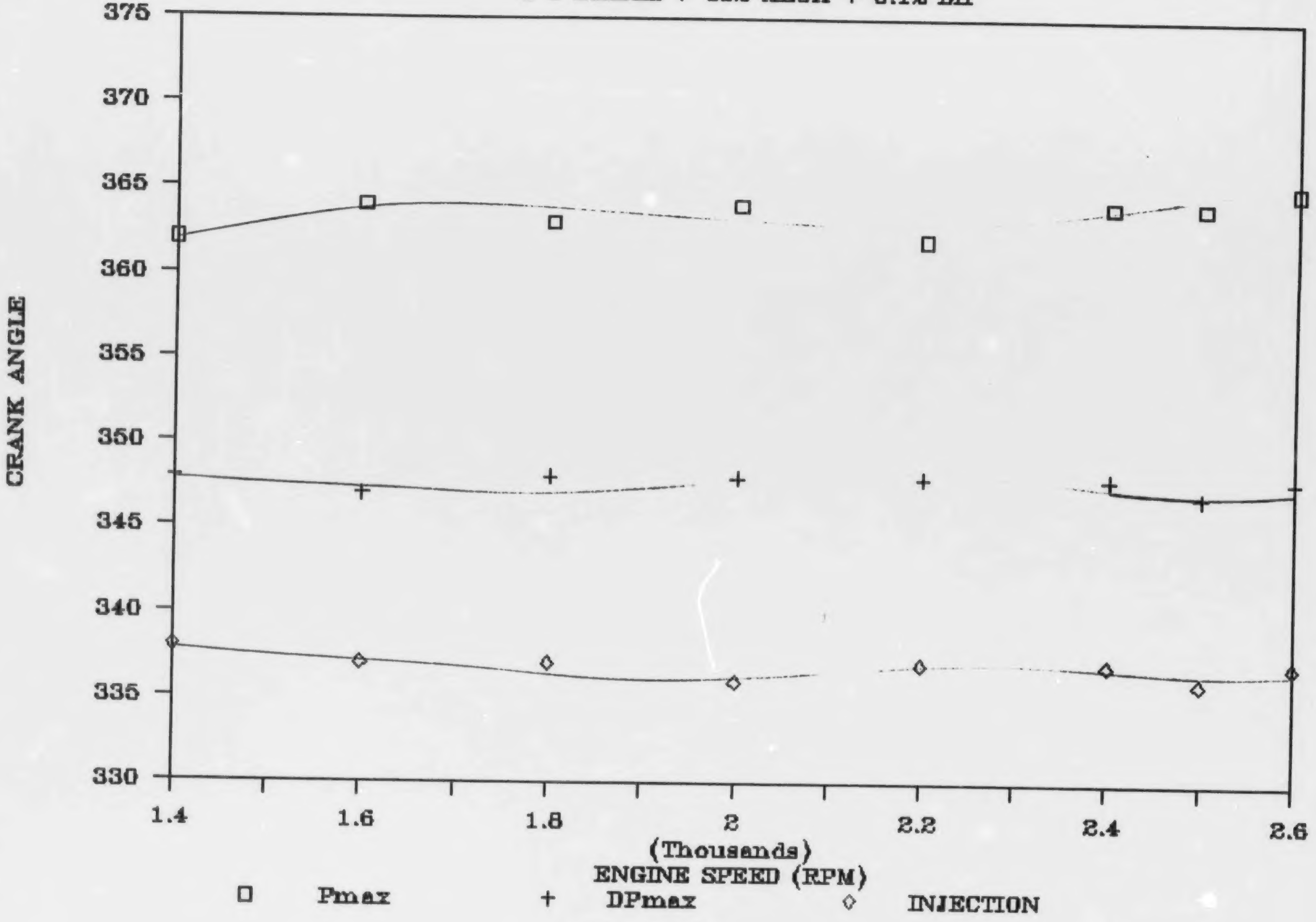
TIMING OF COMBUSTION EVENTS vs. RPM

MAXIMUM LOAD on 15% METHANOL(#1 DIESEL)



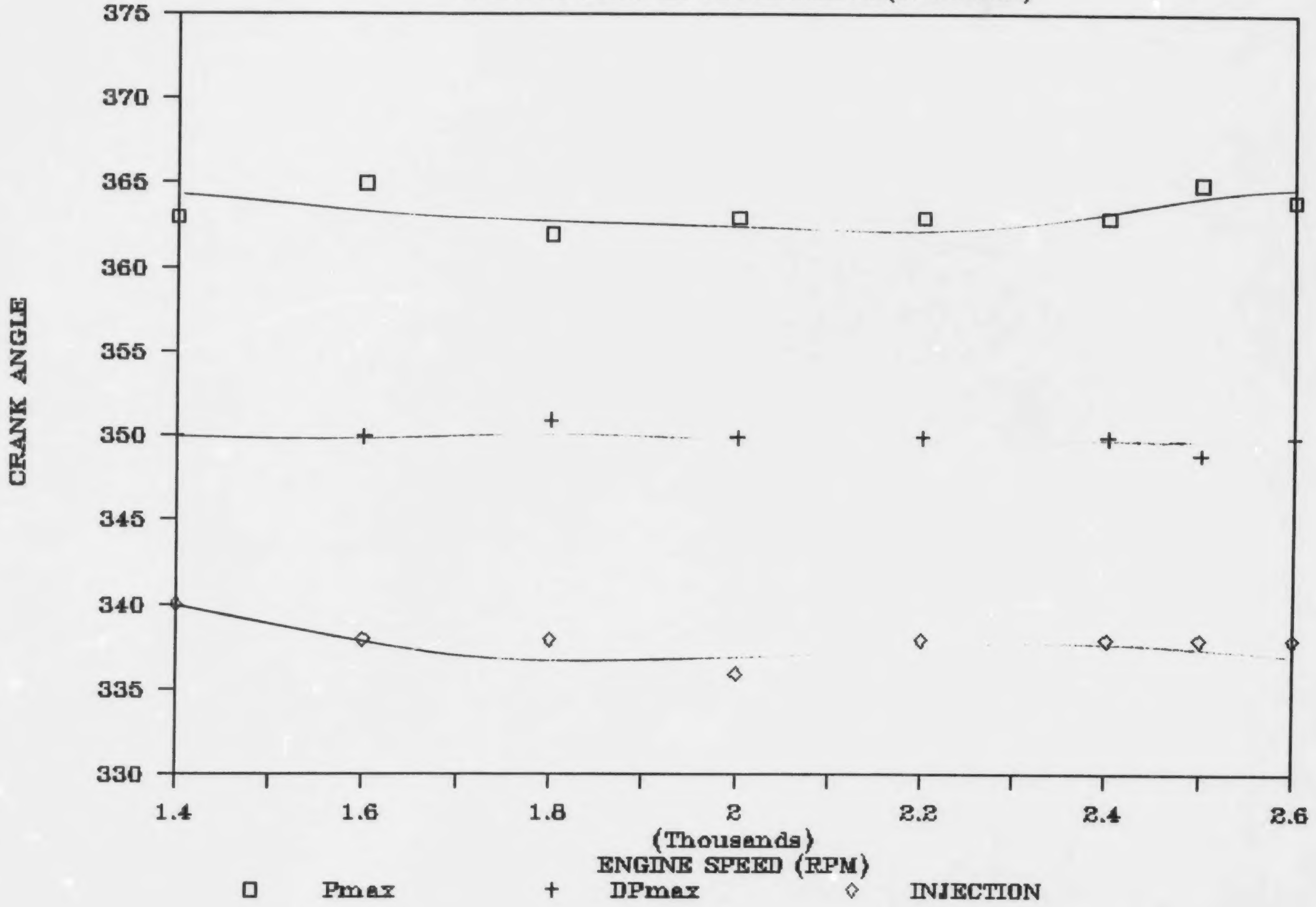
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 15% MEOH + 0.1% DII



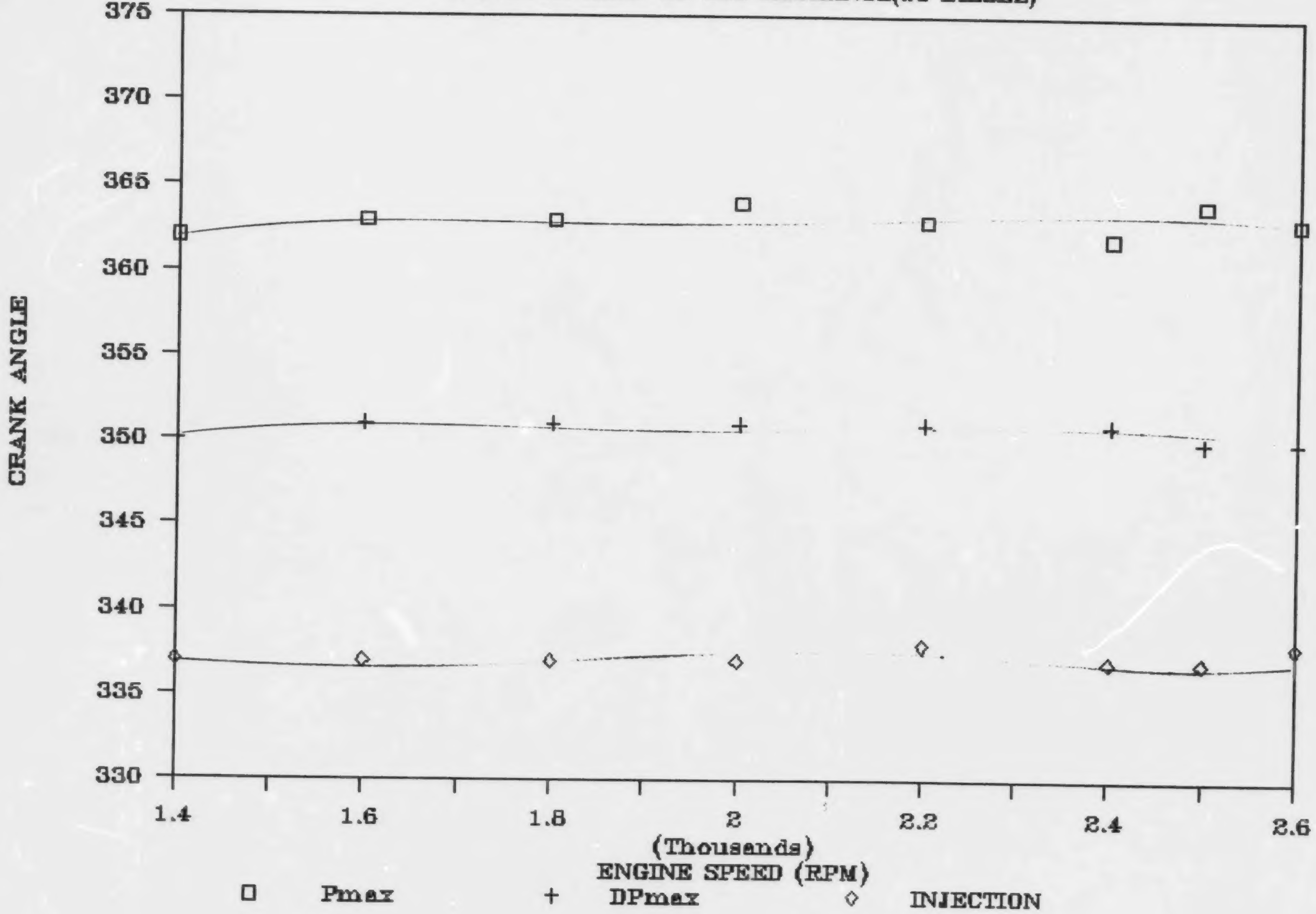
TIMING OF COMBUSTION EVENTS vs. RPM

MAXIMUM LOAD on 20% METHANOL(#1 DIESEL)



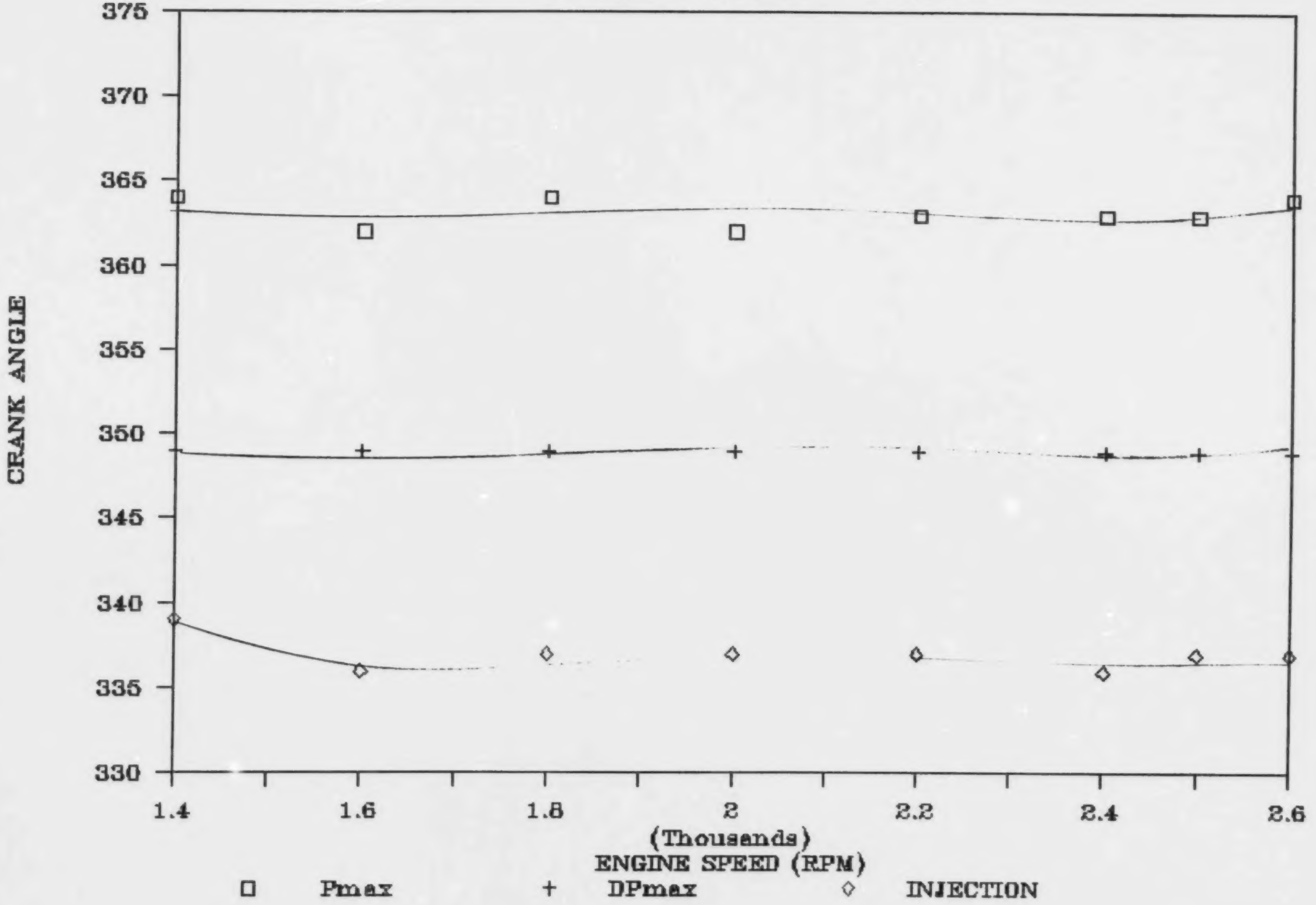
TIMING OF COMBUSTION EVENTS vs. RPM

MAXIMUM LOAD on 25% METHANOL(#1 DIESEL)



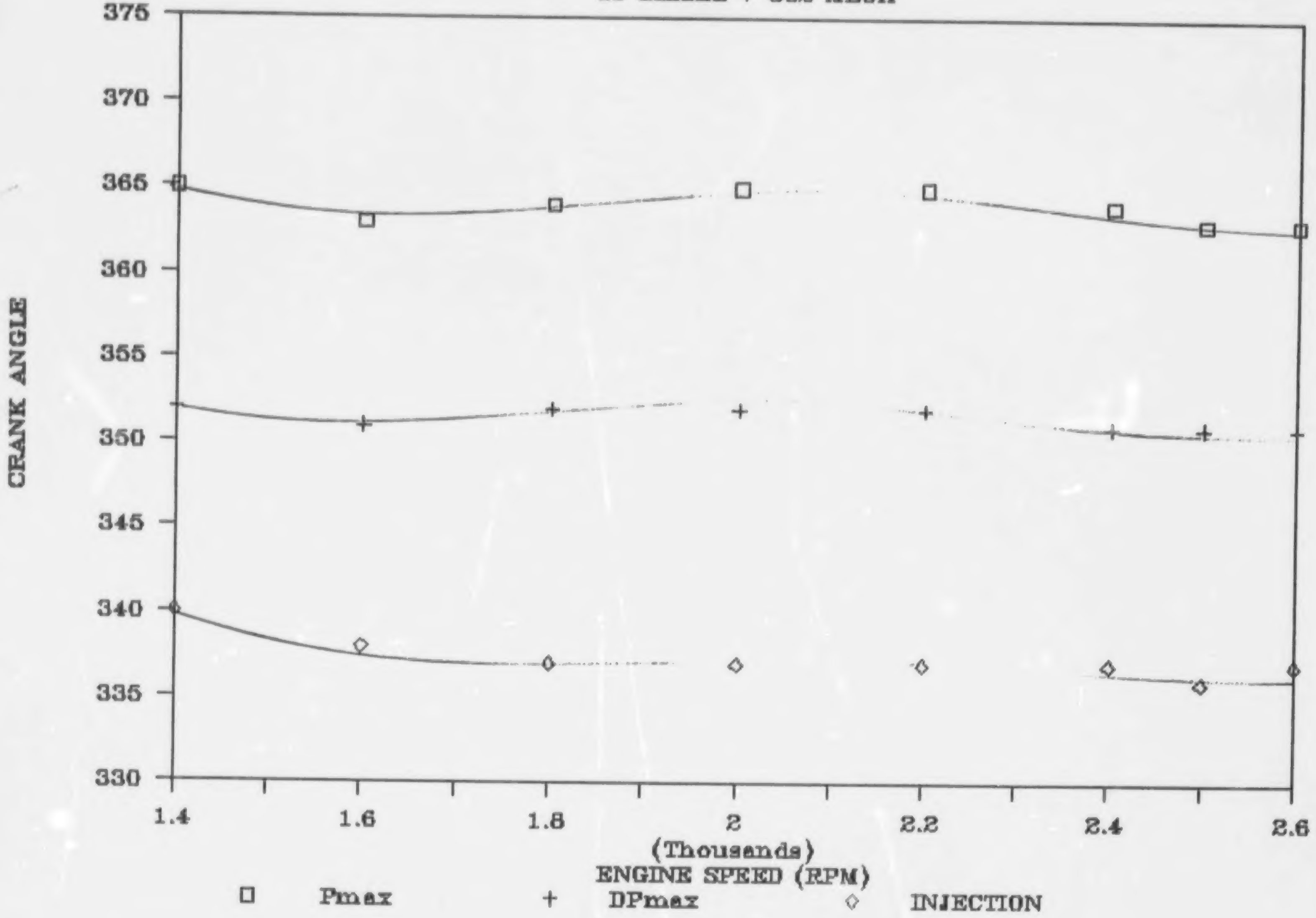
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 25% MEOH + 0.2% DII



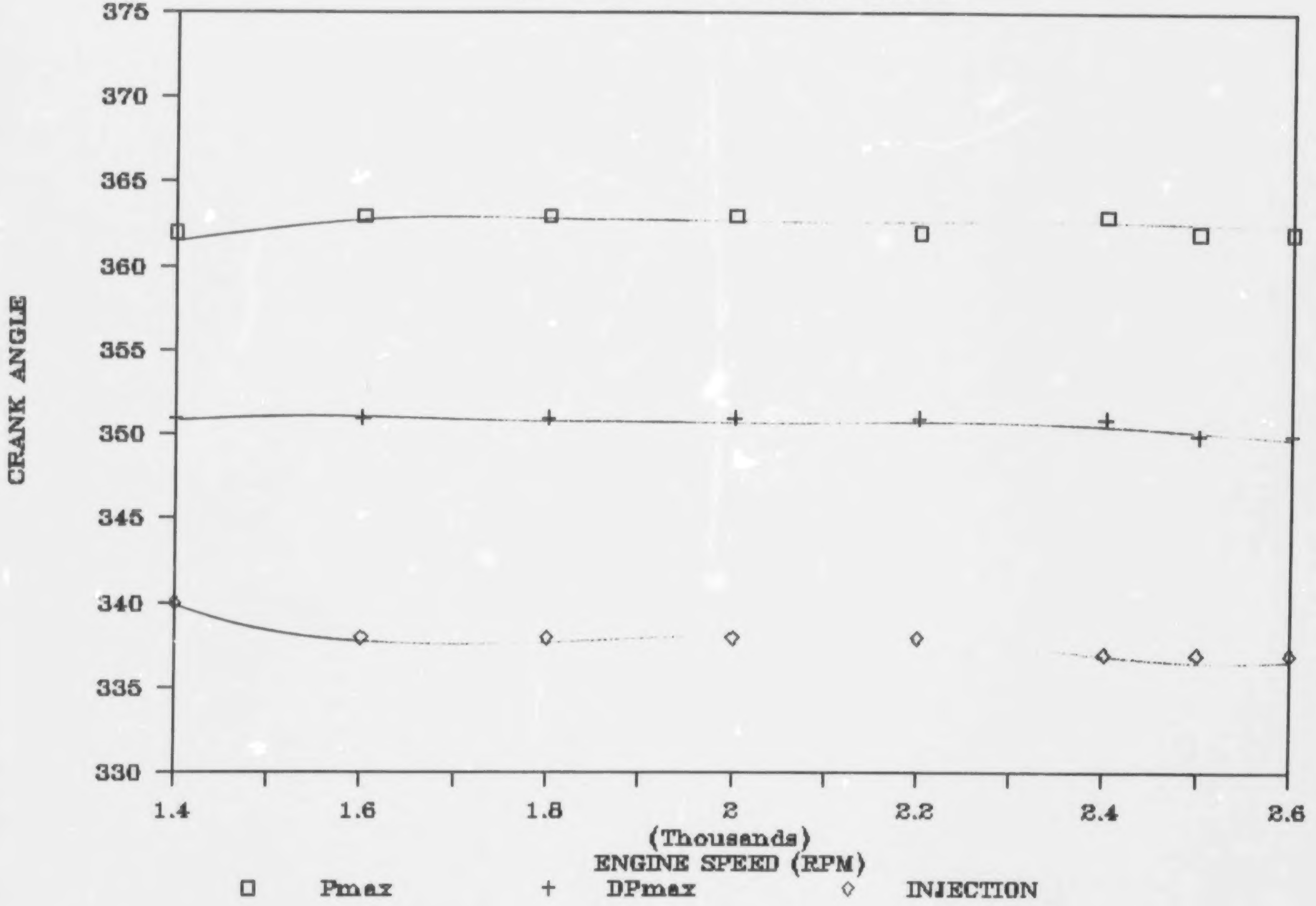
TIMING OF COMBUSTION EVENTS vs. RPM

#1 DIESEL + 30% MEOH



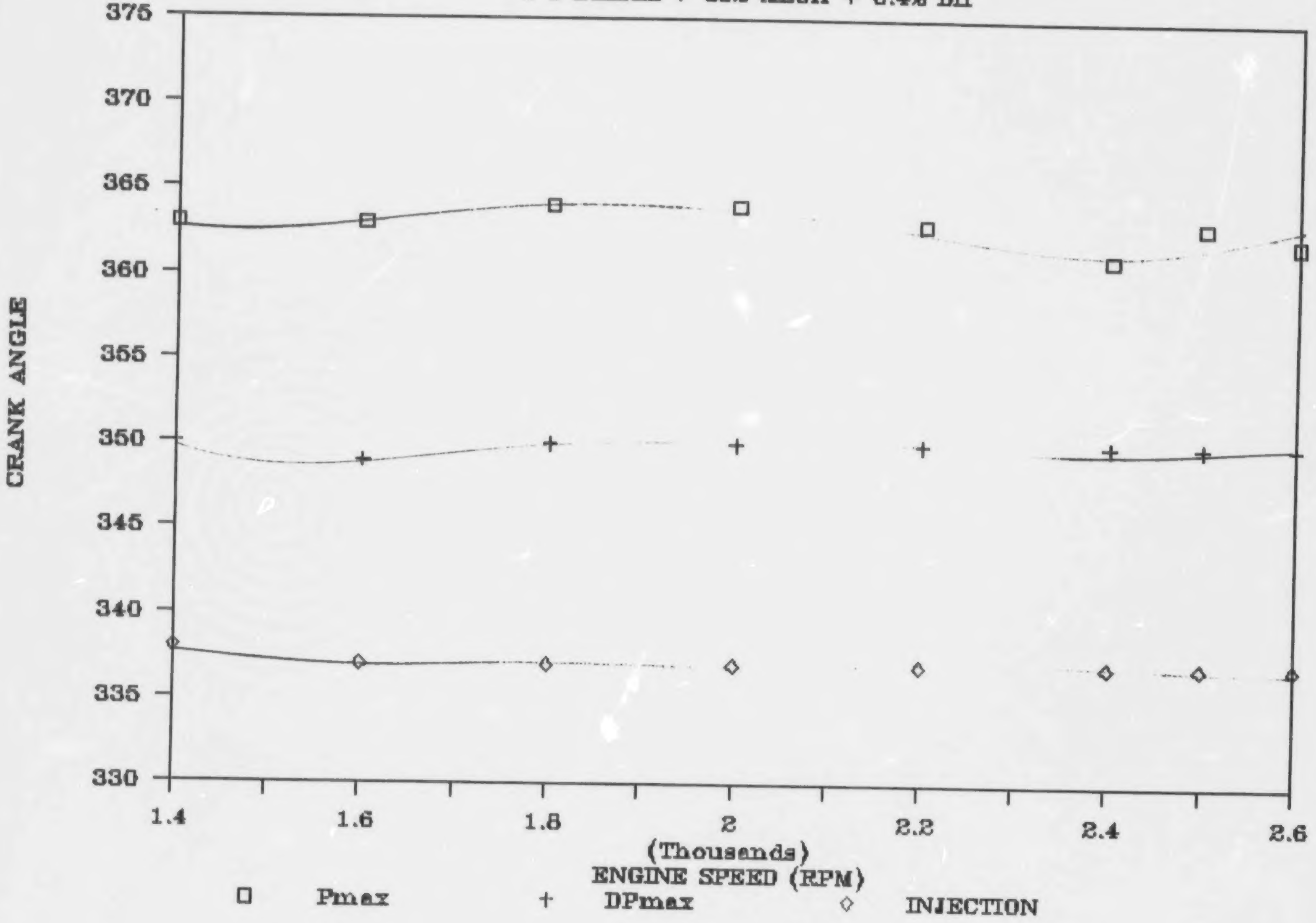
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 30% MEOH + 0.2% DII



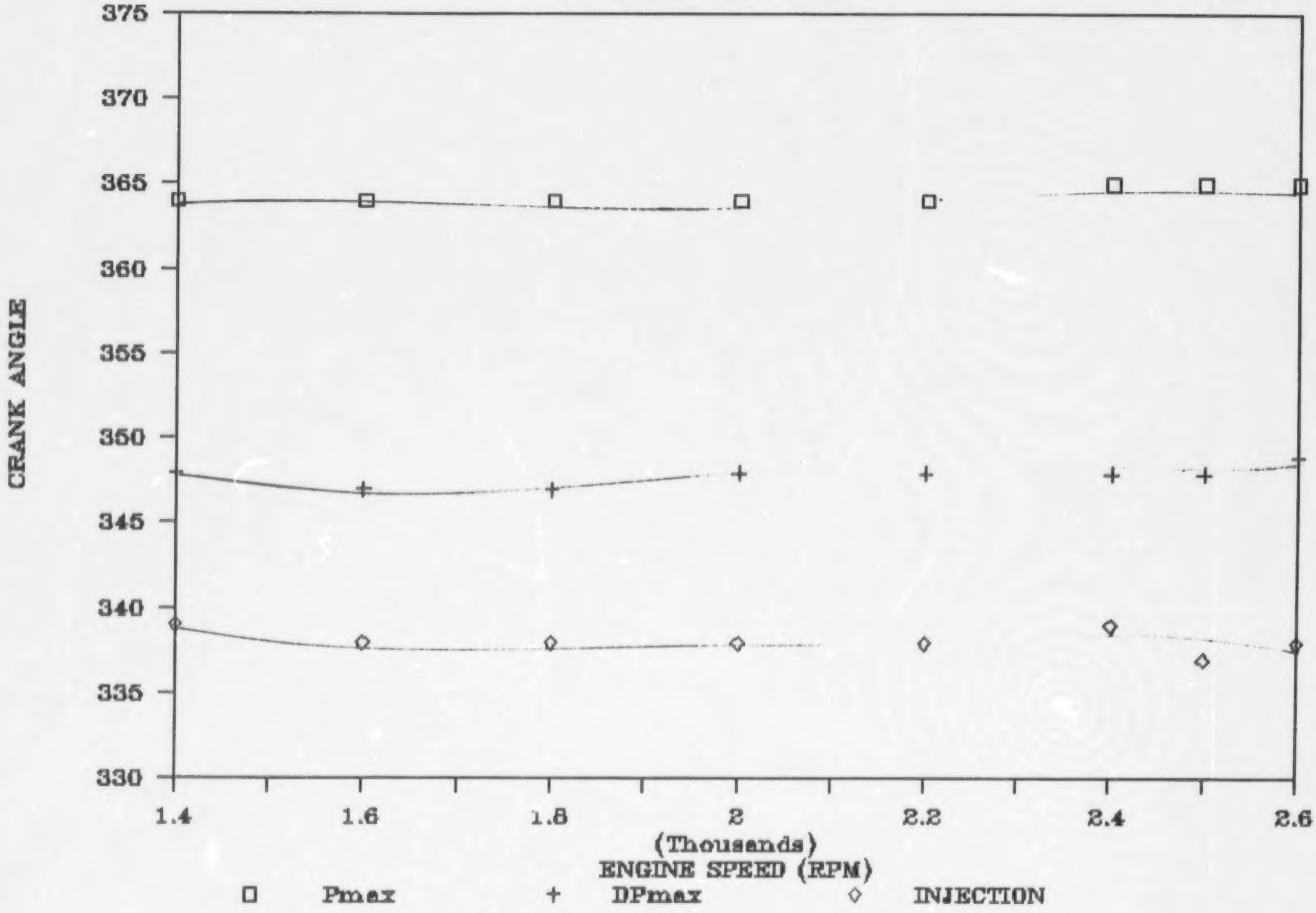
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 30% MEOH + 0.4% DII



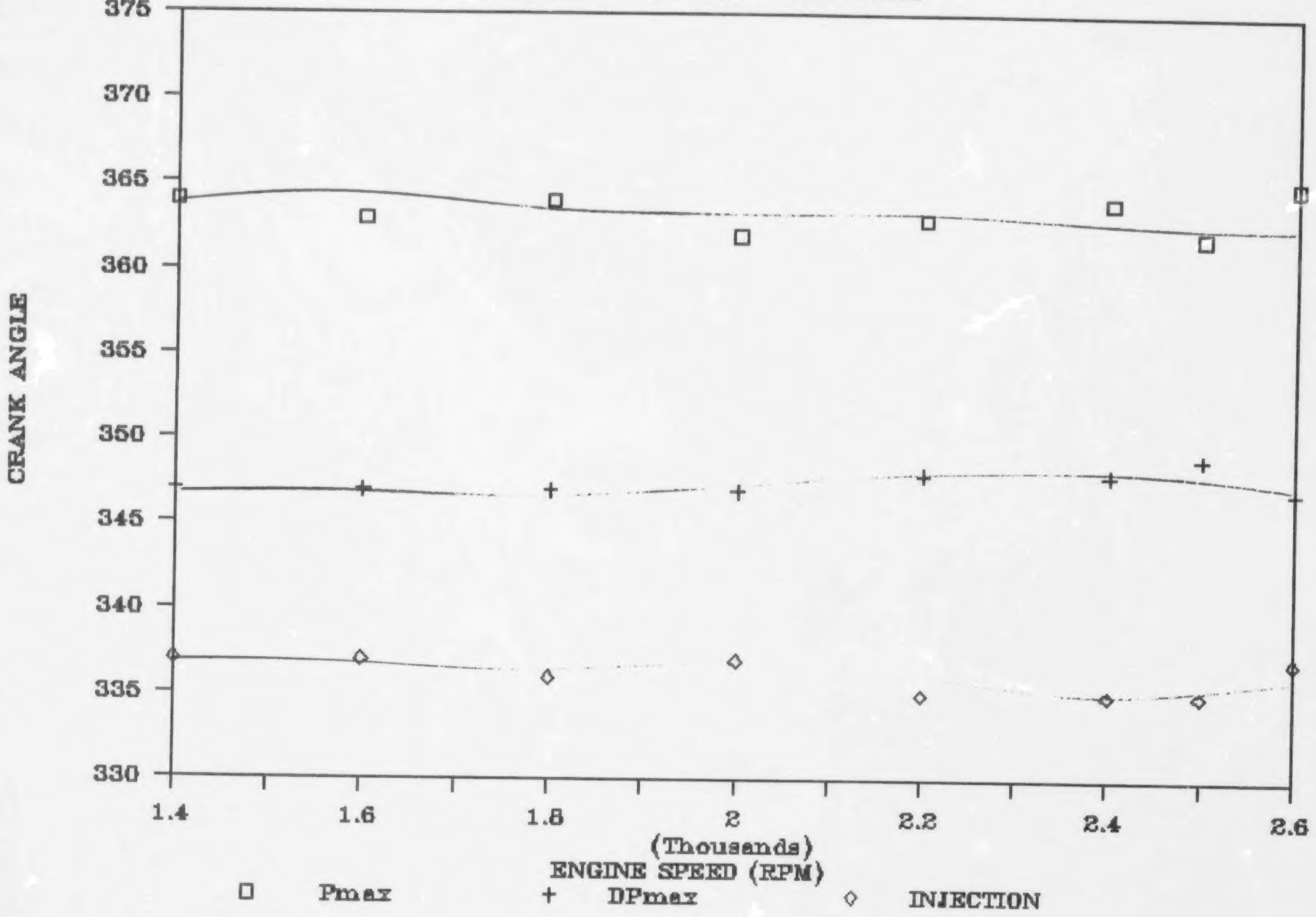
TIMING OF COMBUSTION EVENTS vs. RPM

1 DIESEL + 5% H20



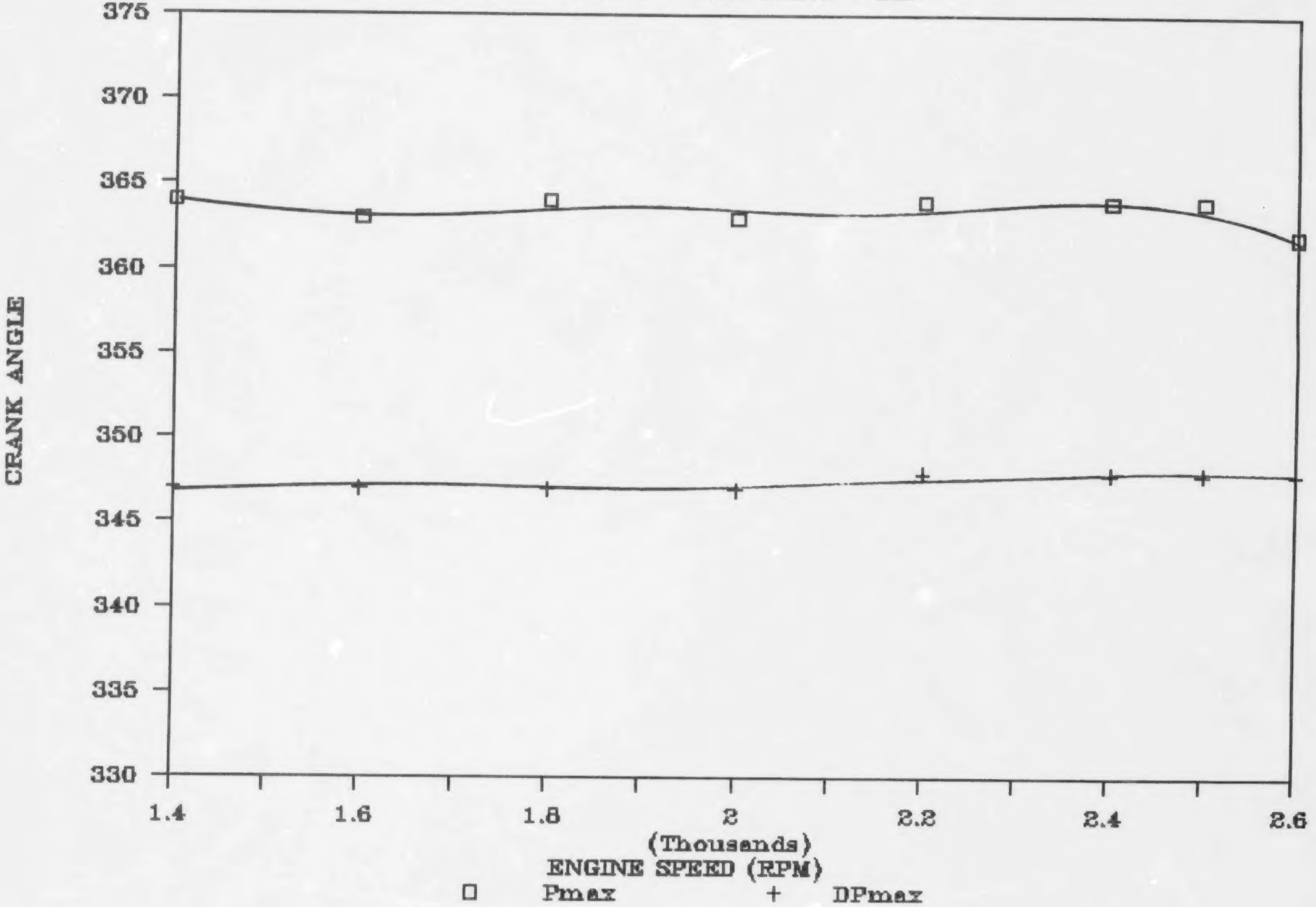
TIMING OF COMBUSTION EVENTS vs. RPM

#1 DIESEL + 5% H20 + 2.5% DALCO



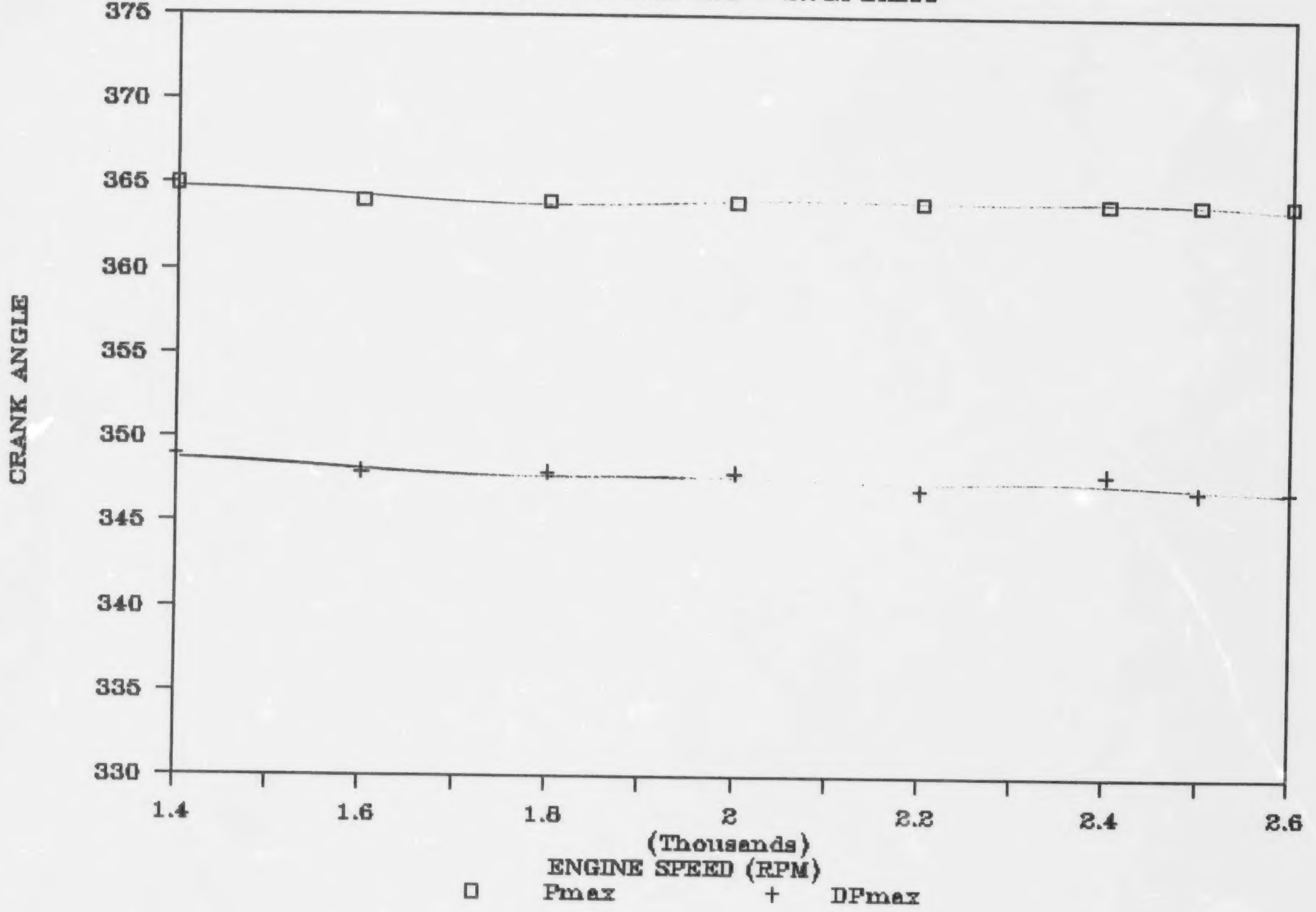
TIMING OF COMBUSTION EVENTS vs. RPM

#1 + 5% H20 + 2.5% DALCO + DII



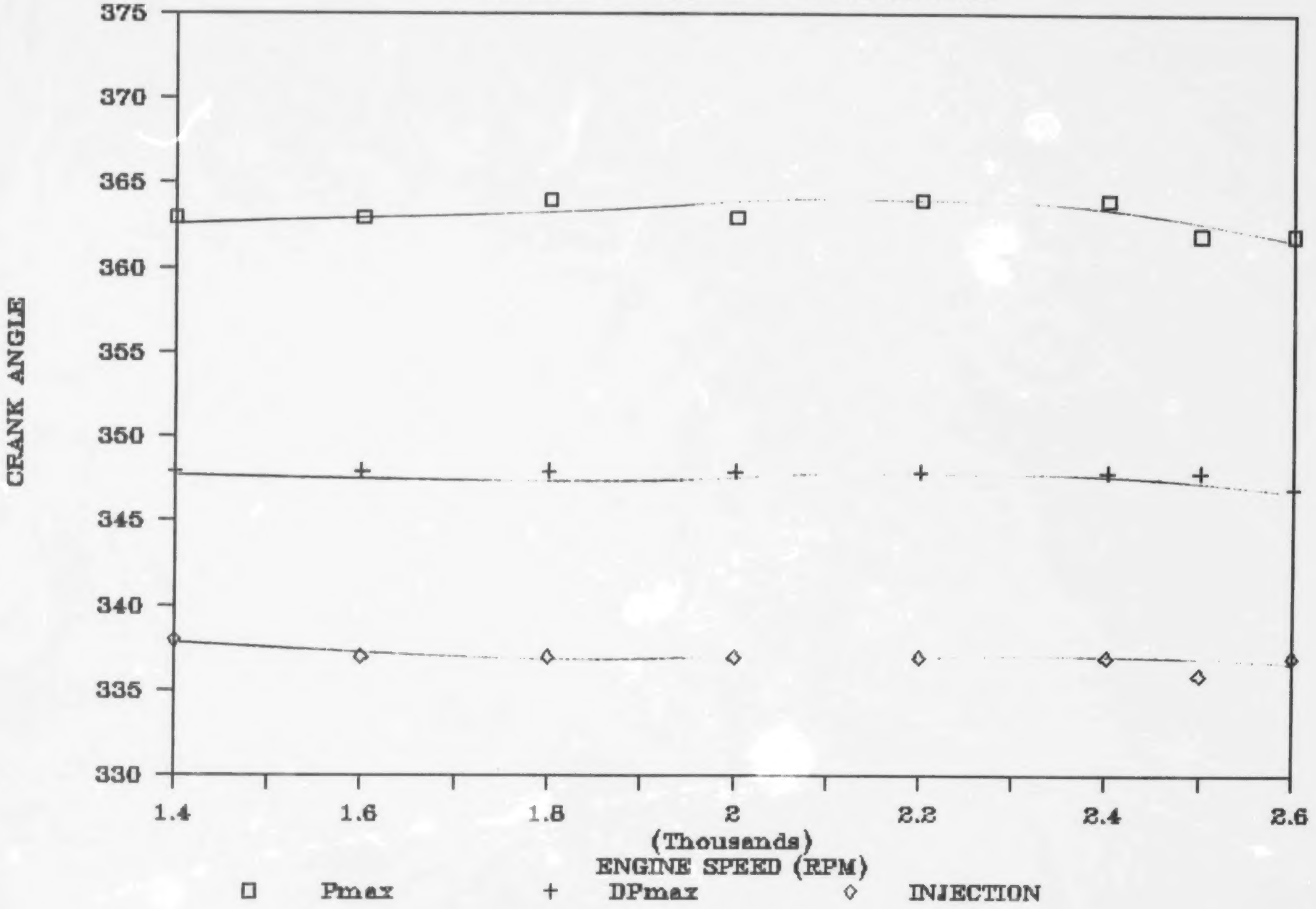
TIMING OF COMBUSTION EVENTS vs. RPM

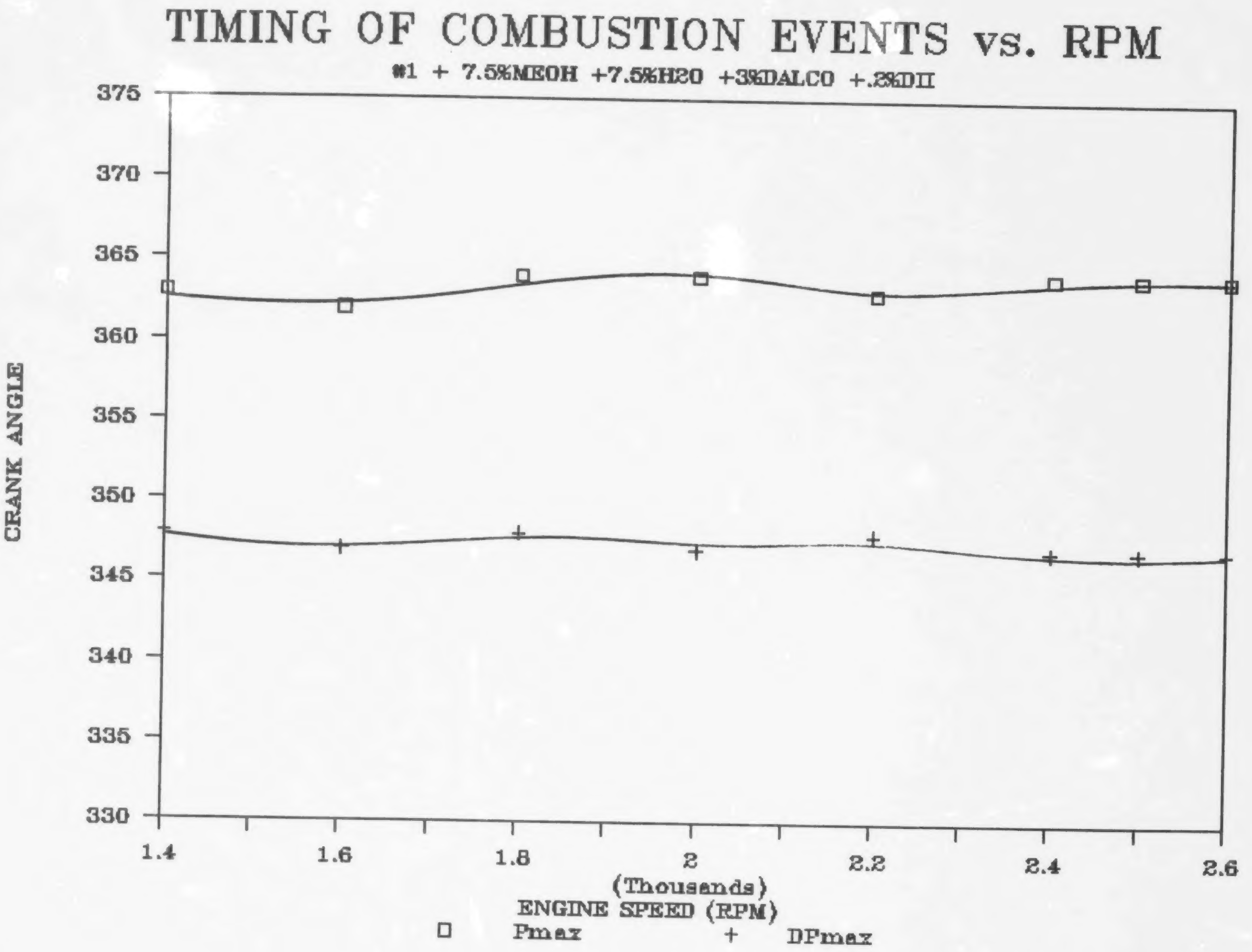
#1 DIESEL + 5.5% H20 + 2.75% DALCO



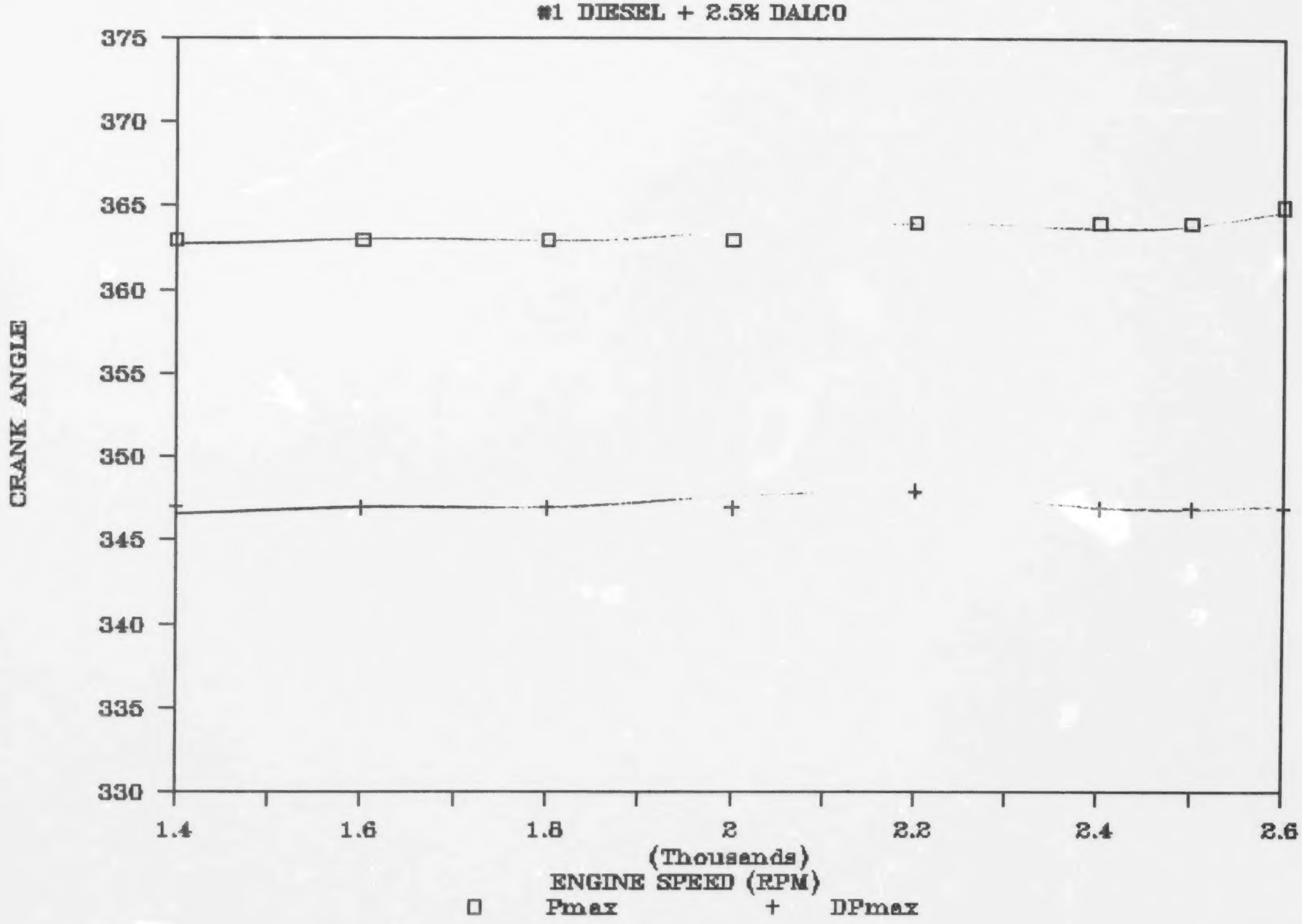
TIMING OF COMBUSTION EVENTS vs. RPM

#1DIESEL + 15%MEOH + 0.15%H2O + DII

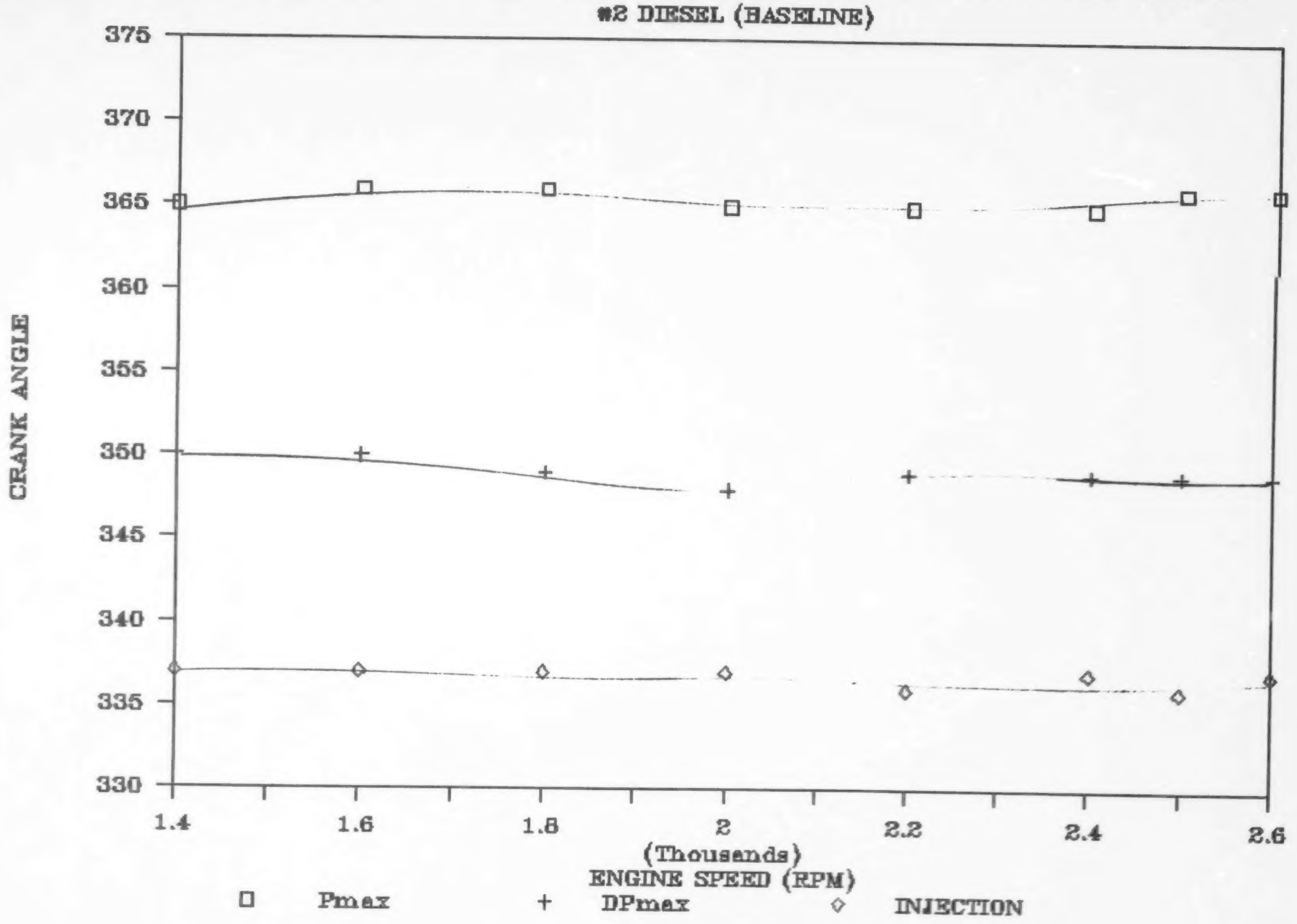



TIMING OF COMBUSTION EVENTS vs. RPM
#1 + 7.5%MEOH +7.5%H2O +3%DALCO +.2%DII
CRANK ANGLE
375
370
365
360
355
350
345
340
335
330
1.4
1.6
1.8
2
2.2
2.4
2.6
(Thousands)
ENGINE SPEED (RPM)
□ Pmax
+ DPmax

TIMING OF COMBUSTION EVENTS vs. RPM

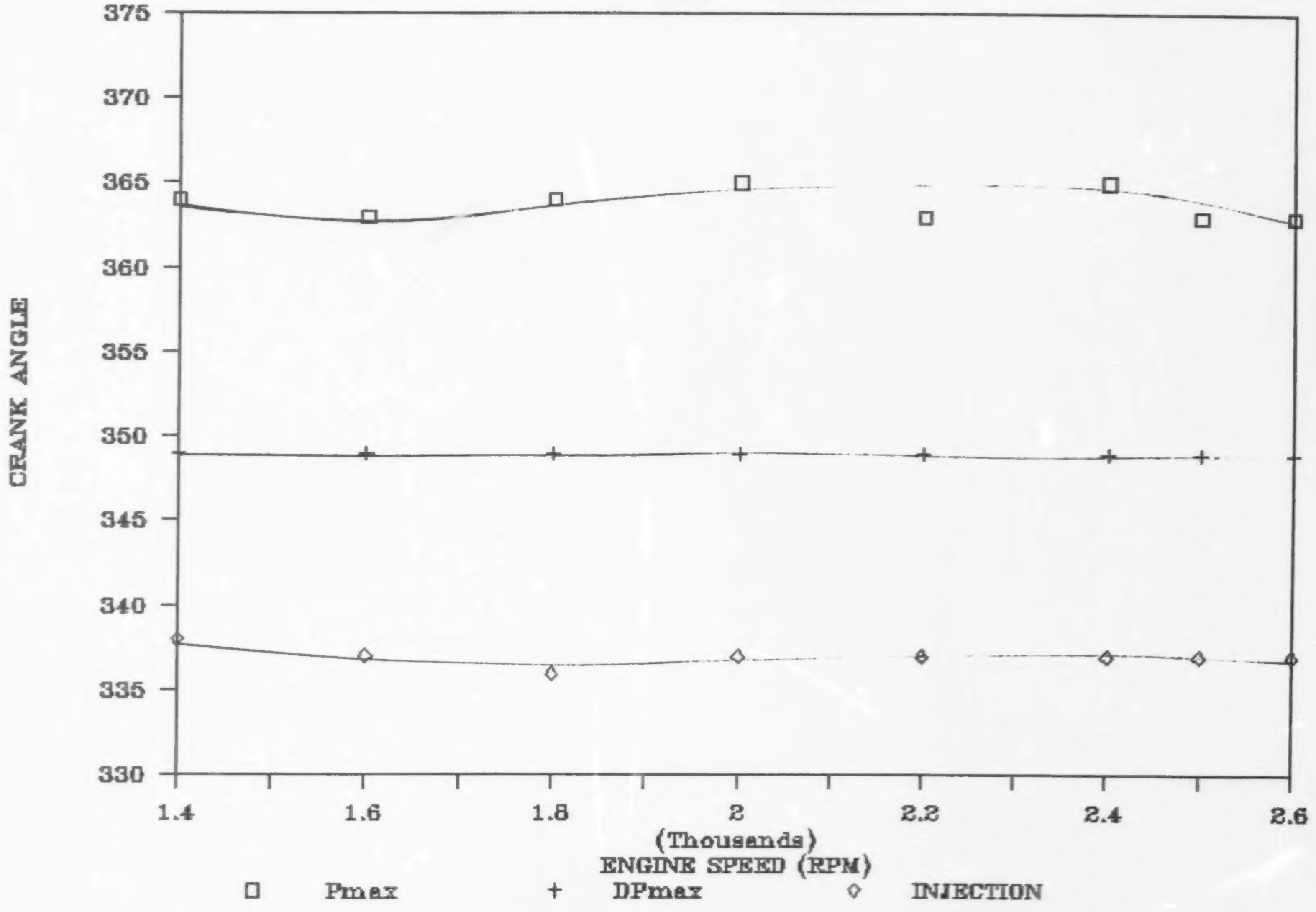


TIMING OF COMBUSTION EVENTS vs. RPM



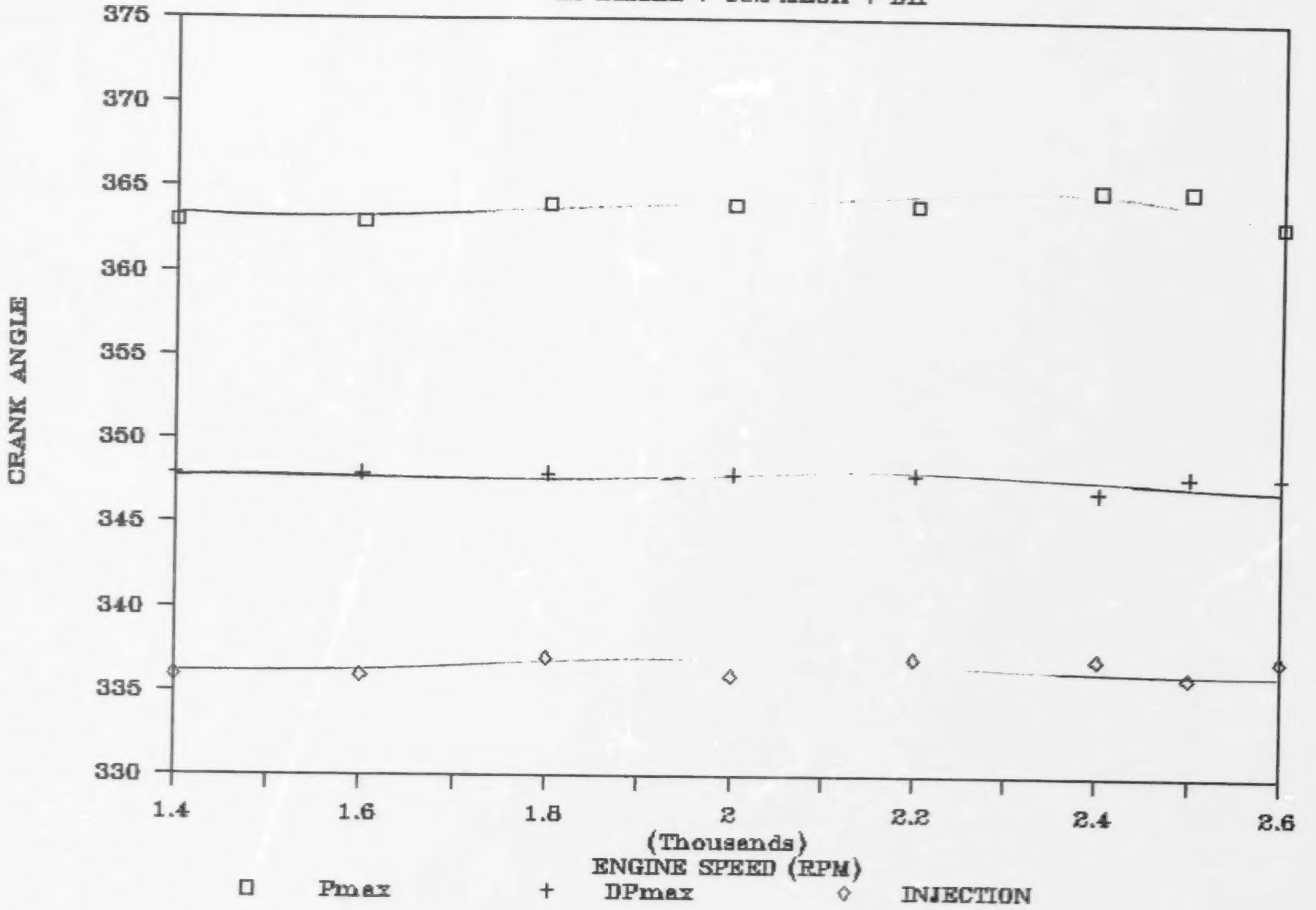
TIMING OF COMBUSTION EVENTS vs. RPM

#2 DIESEL + 15% MEOH



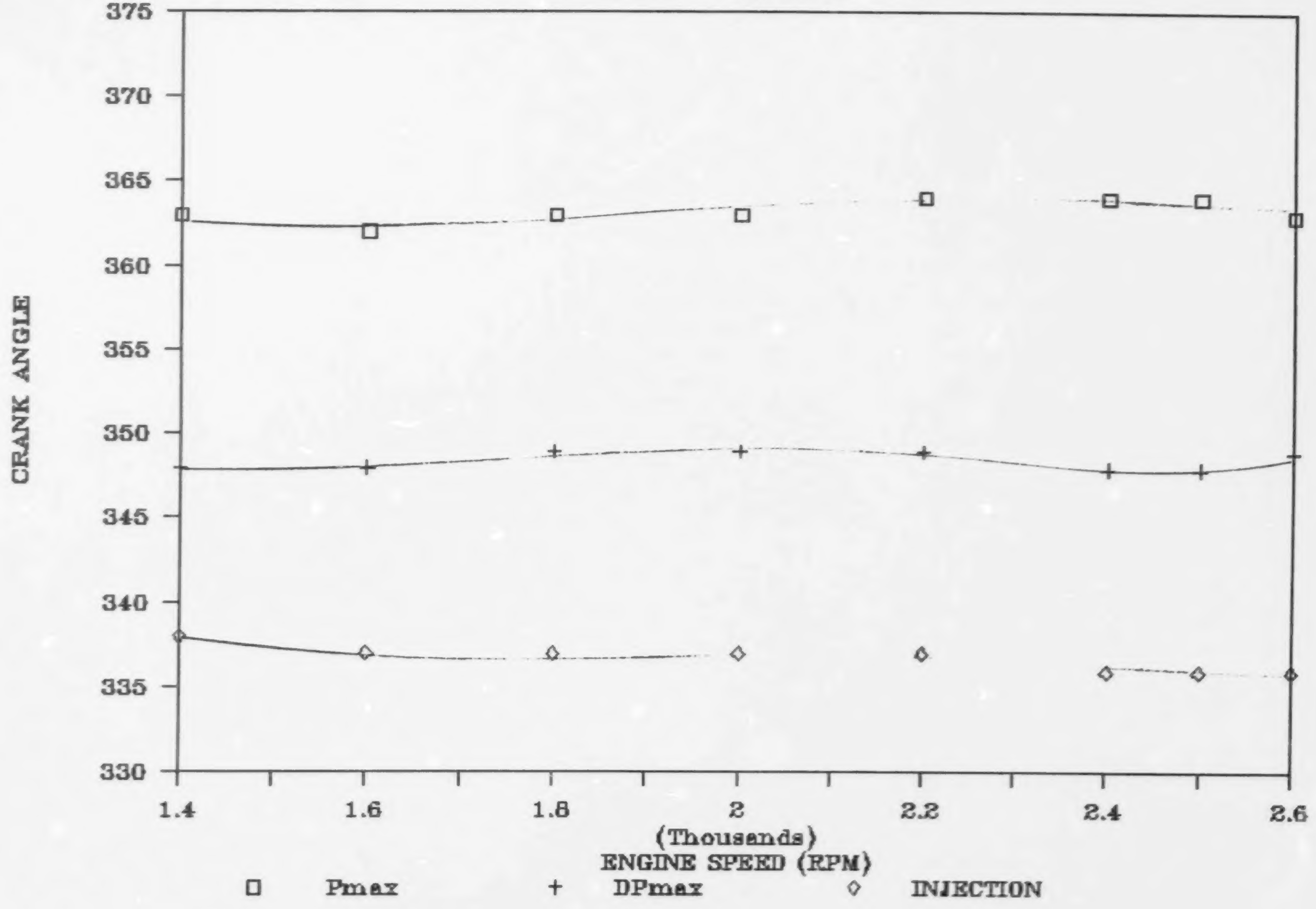
TIMING OF COMBUSTION EVENTS vs. RPM

#2 DIESEL + 15% MEOH + DII



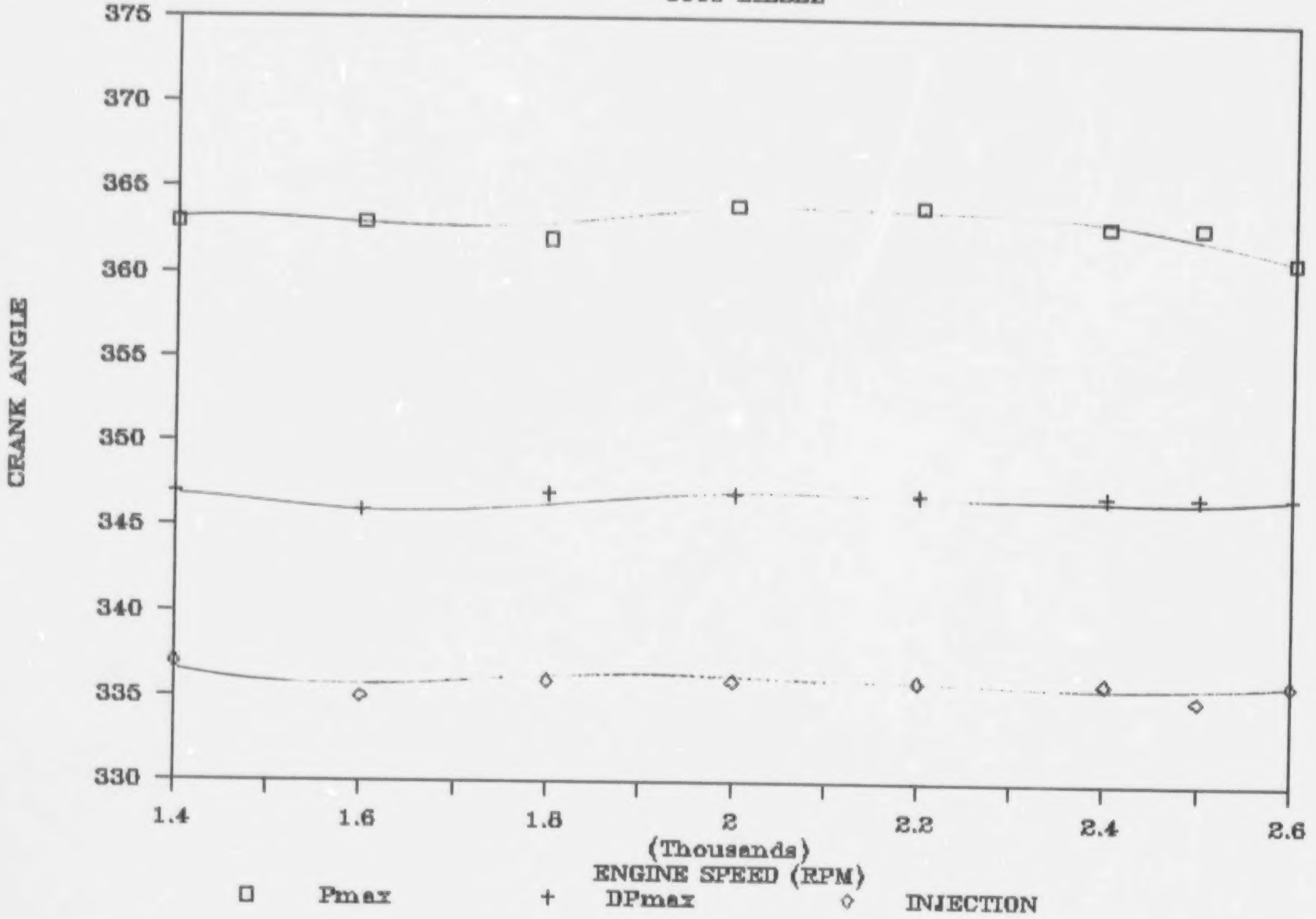
TIMING OF COMBUSTION EVENTS vs. RPM

#2 DIESEL + 20% MEOH + DII



TIMING OF COMBUSTION EVENTS vs. RPM

1990 DIESEL

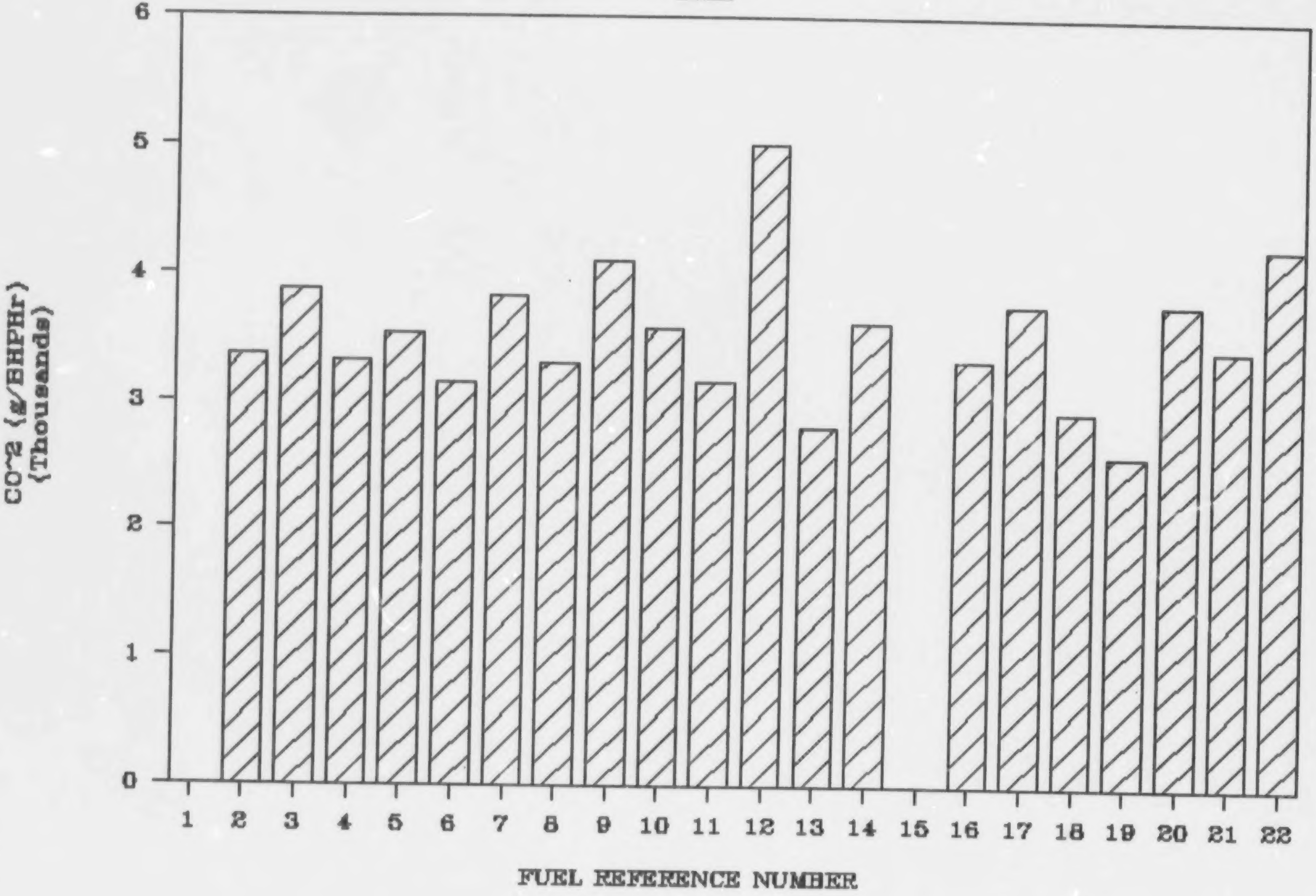


APPENDIX B

EMISSIONS DATA

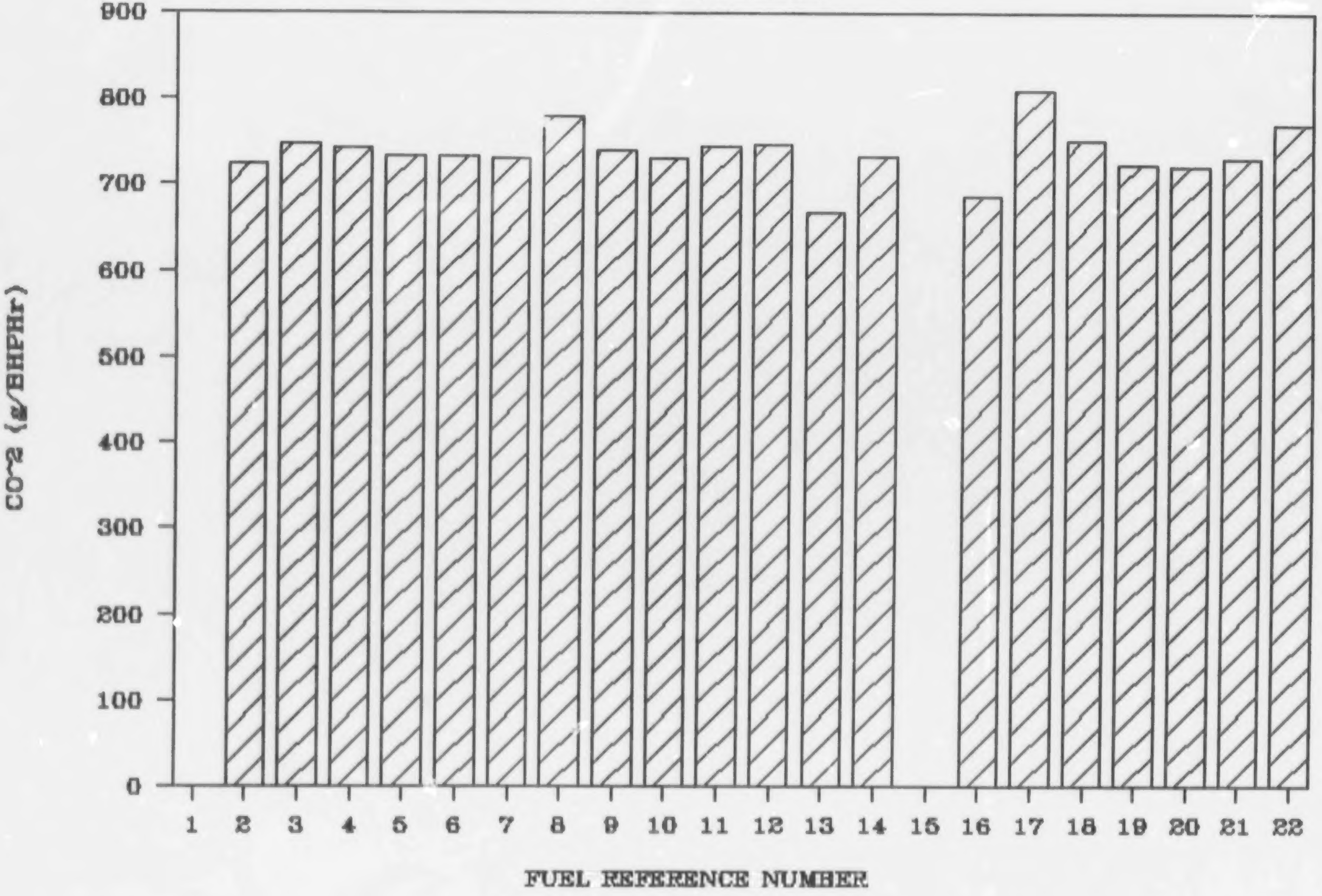
CARBON DIOXIDE EMISSIONS (g/BHPHr)

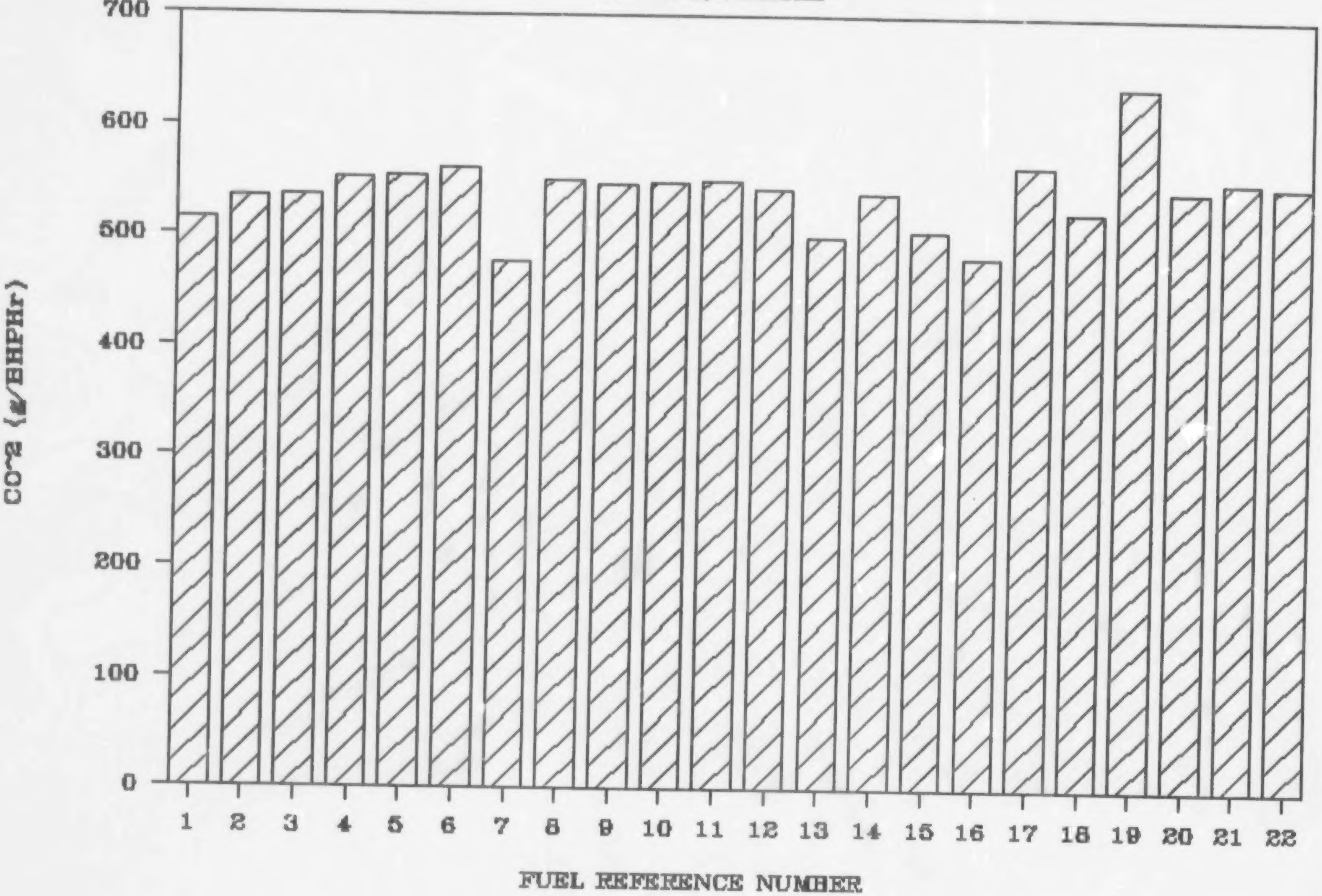
IDLE



CARBON DIOXIDE EMISSIONS (g/BHPHr)

1400RPM/25%LOAD



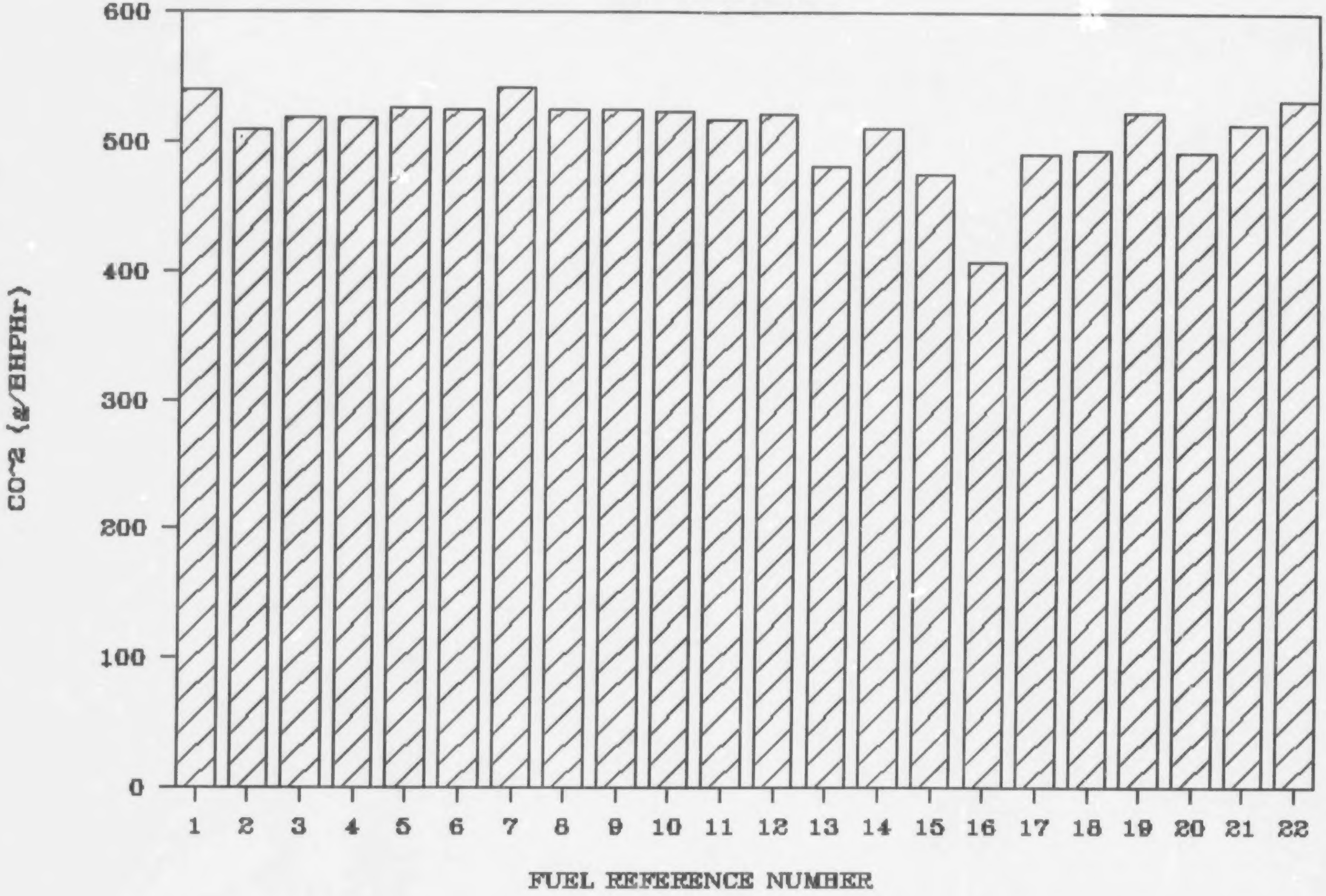


CARBON DIOXIDE EMISSIONS (g/BHPHr)

1800RPM/75%LOAD

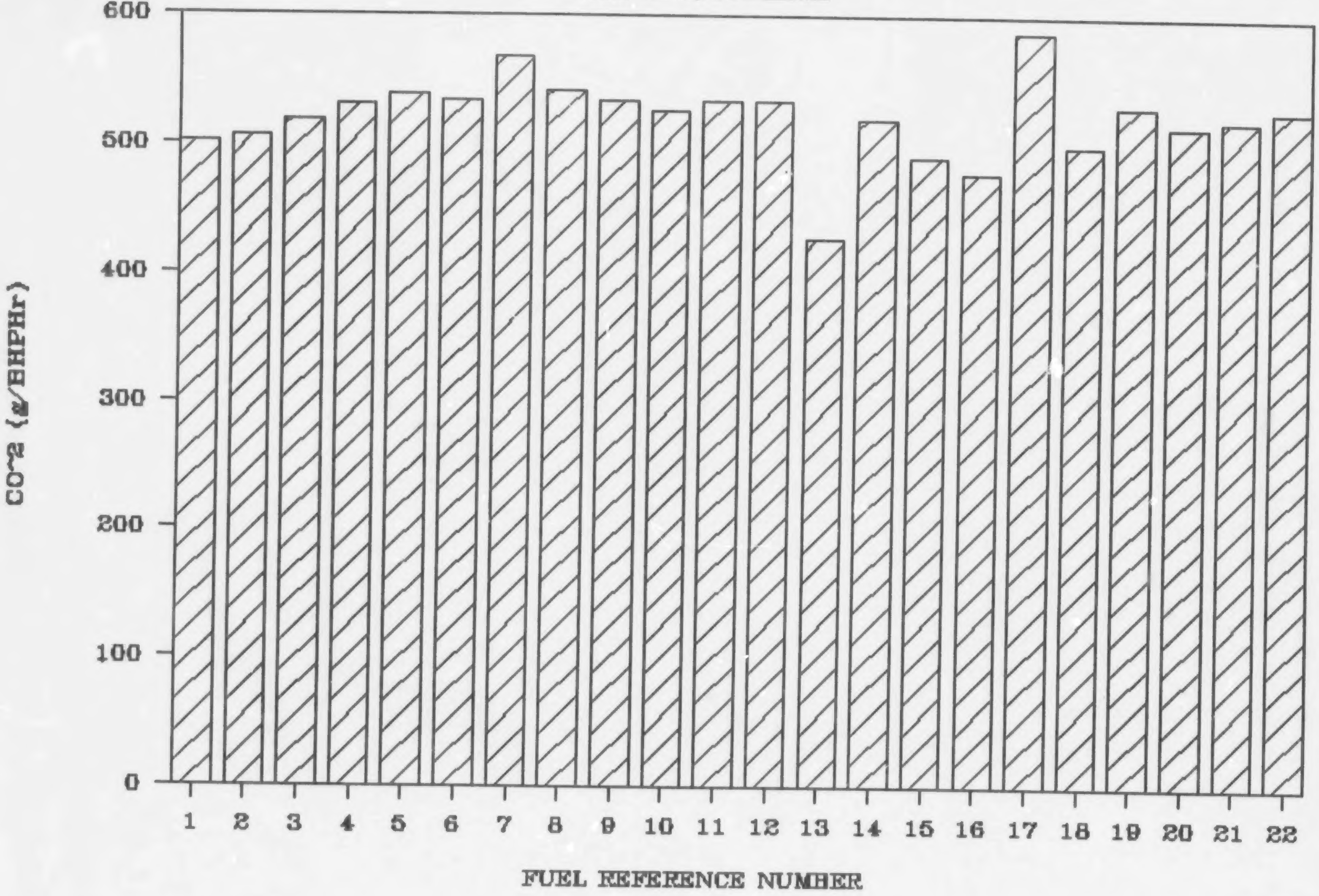
CARBON DIOXIDE EMISSIONS (g/BHPHr)

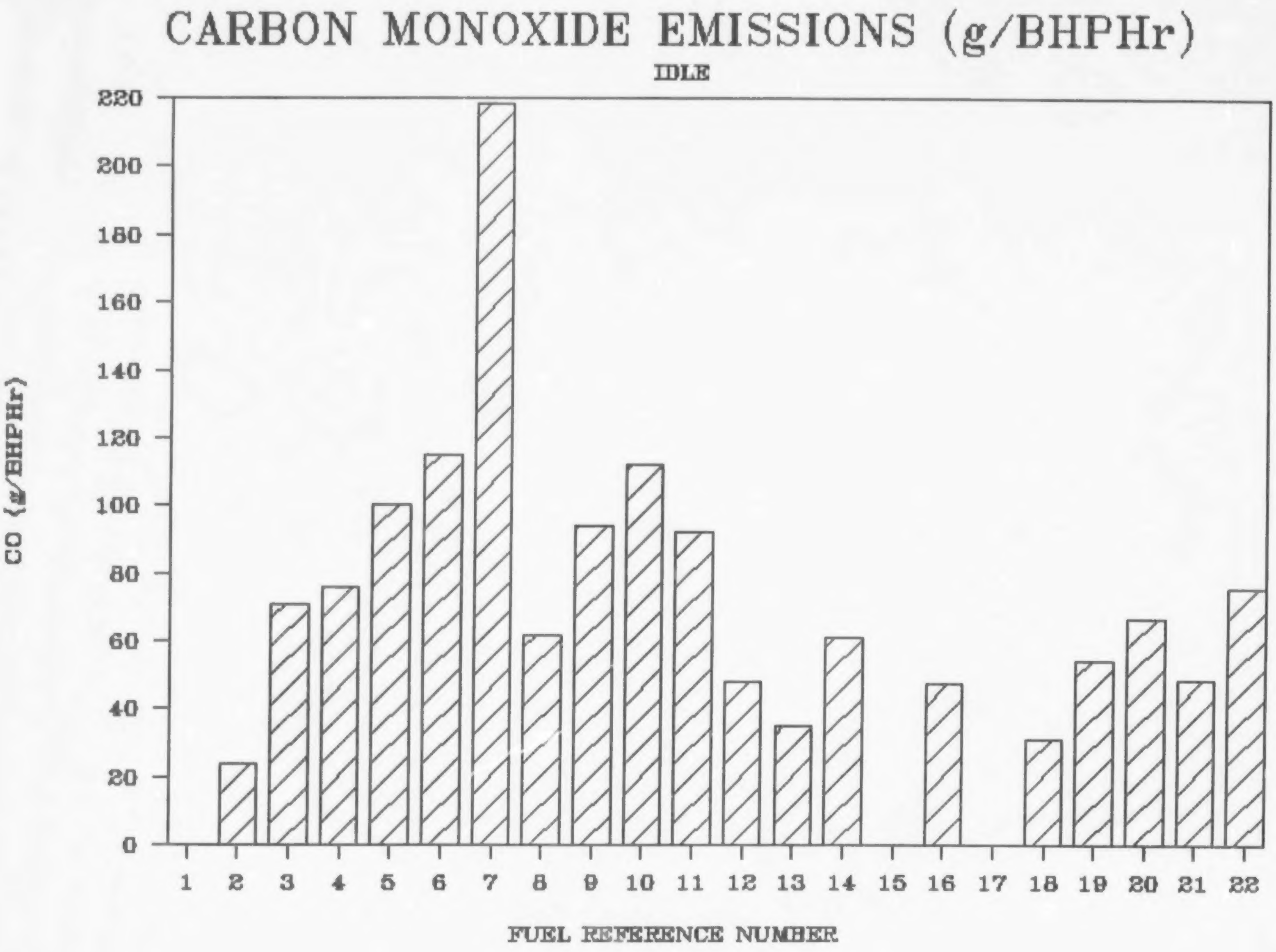
1600RPM/100%LOAD



CARBON DIOXIDE EMISSIONS (g/BHPHr)

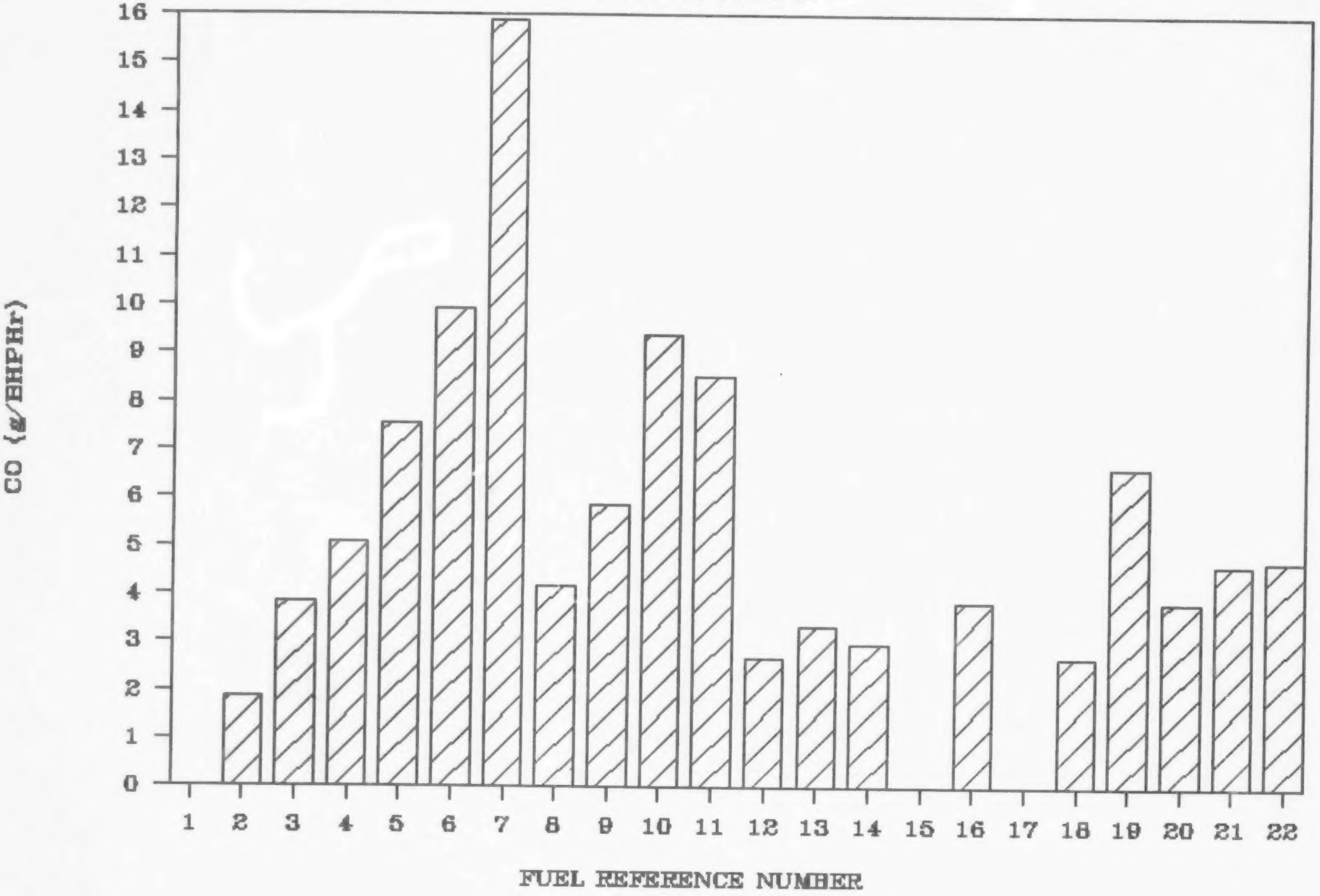
2200RPM/100%LOAD




CARBON MONOXIDE EMISSIONS (g/BHPHr)
IDLE
CO (g/BHPHr)
220
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
FUEL REFERENCE NUMBER

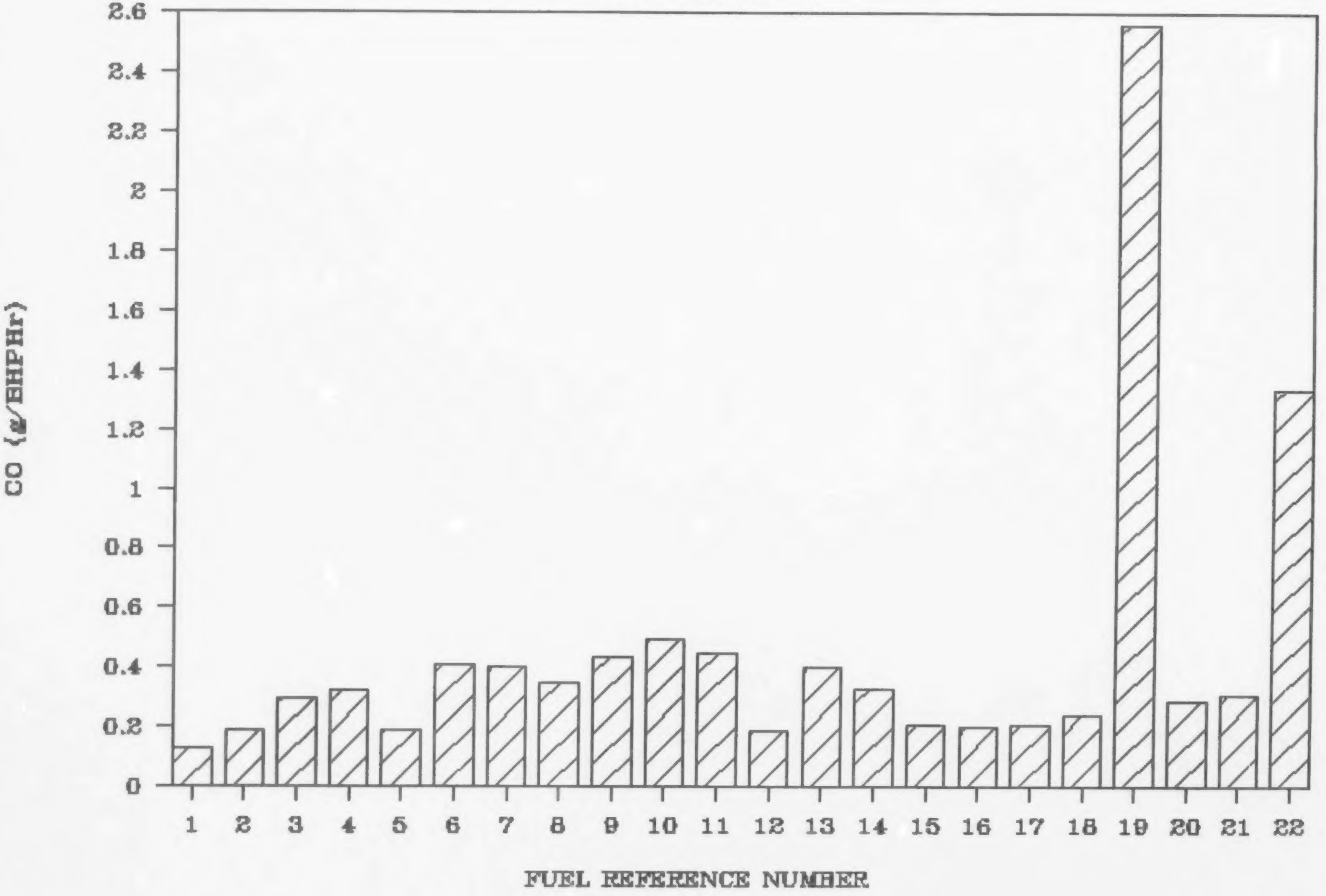
CARBON MONOXIDE EMISSIONS (g/BHPHr)

1400RPM/25%LOAD



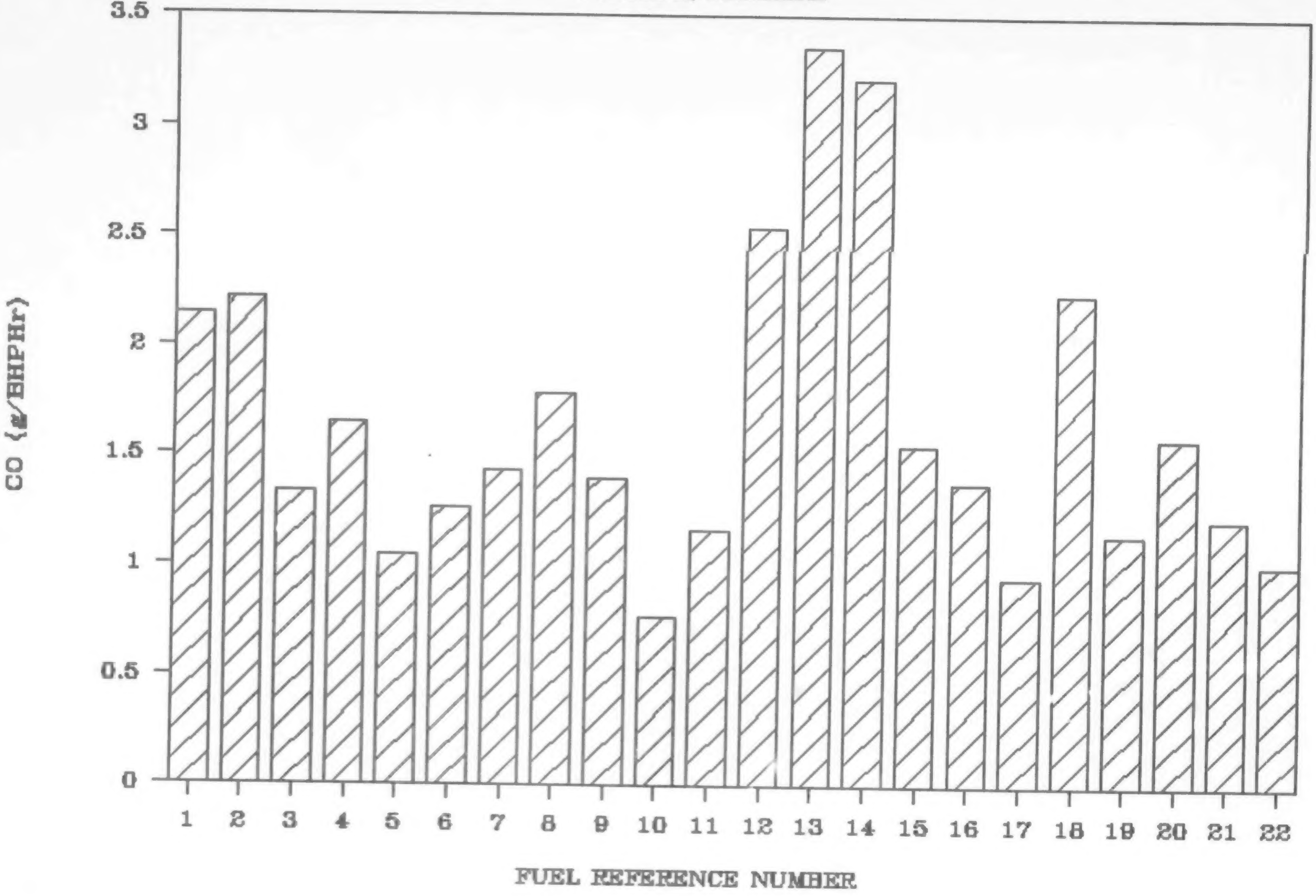
CARBON MONOXIDE EMISSIONS (g/BHPHr)

1800RPM/75%LOAD



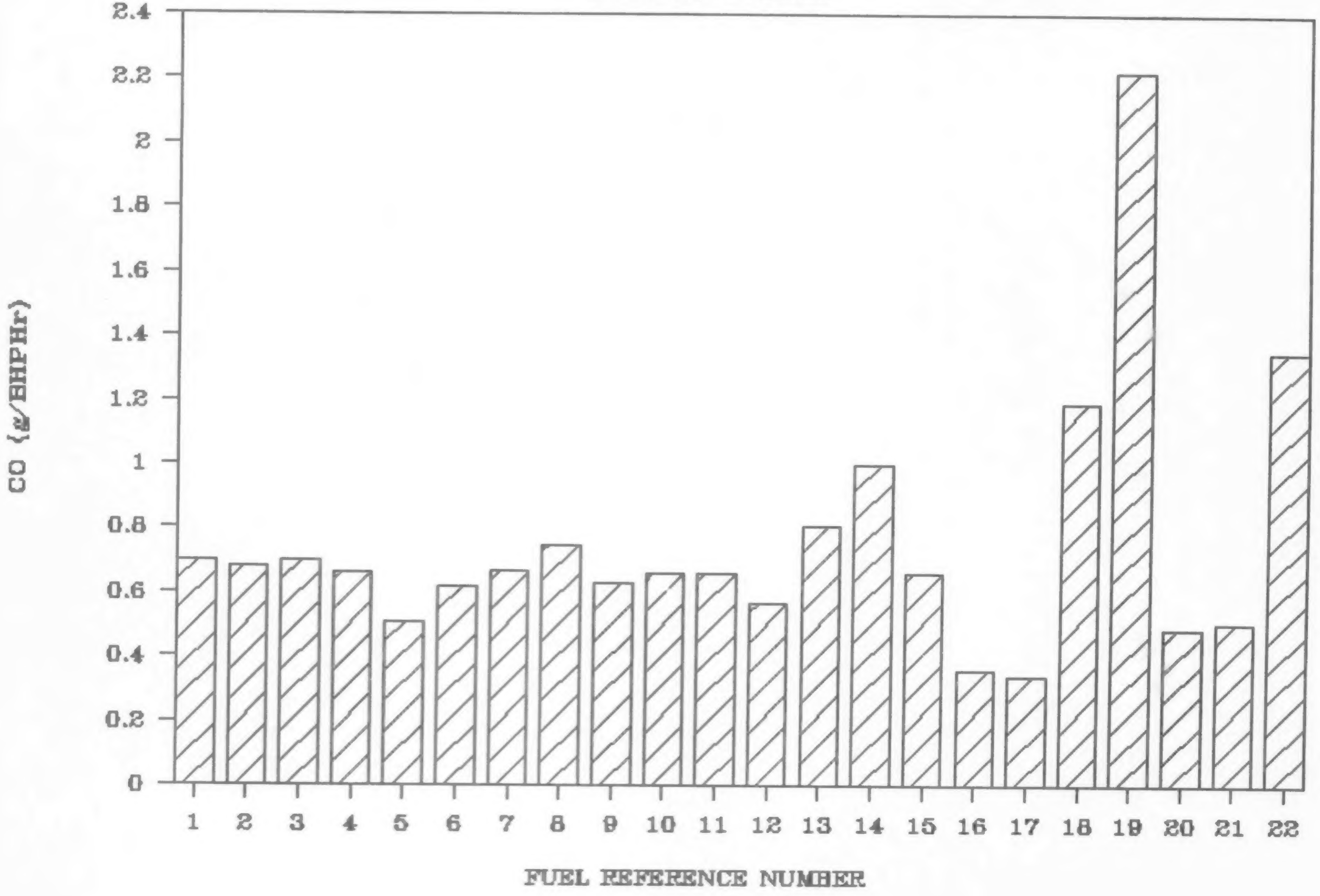
CARBON MONOXIDE EMISSIONS (g/BHPHr)

1600RPM/100%LOAD



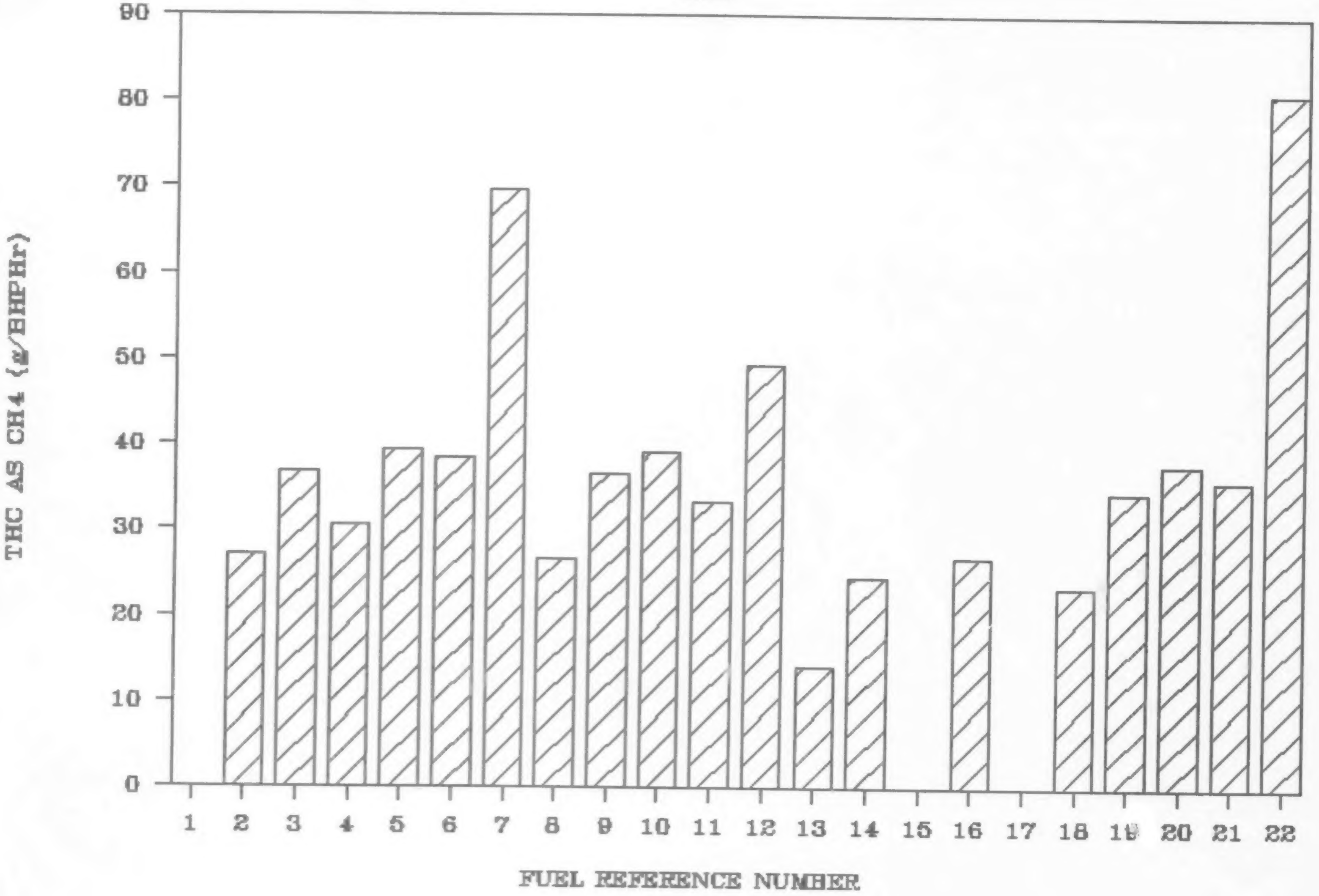
CARBON MONOXIDE EMISSIONS (g/BHPHr)

2200RPM/100%LOAD



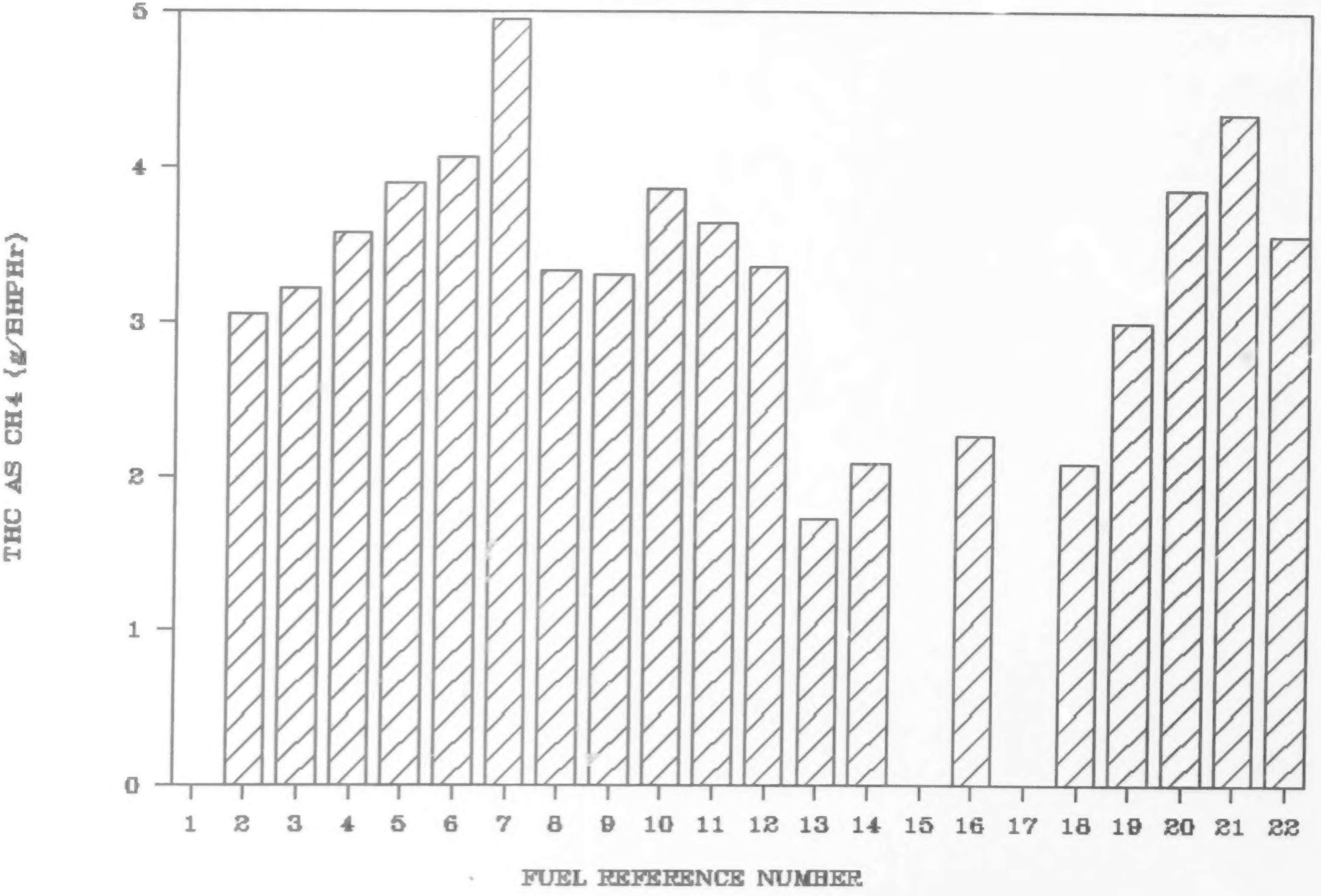
THC AS CH4 EMISSIONS (g/BHPHr)

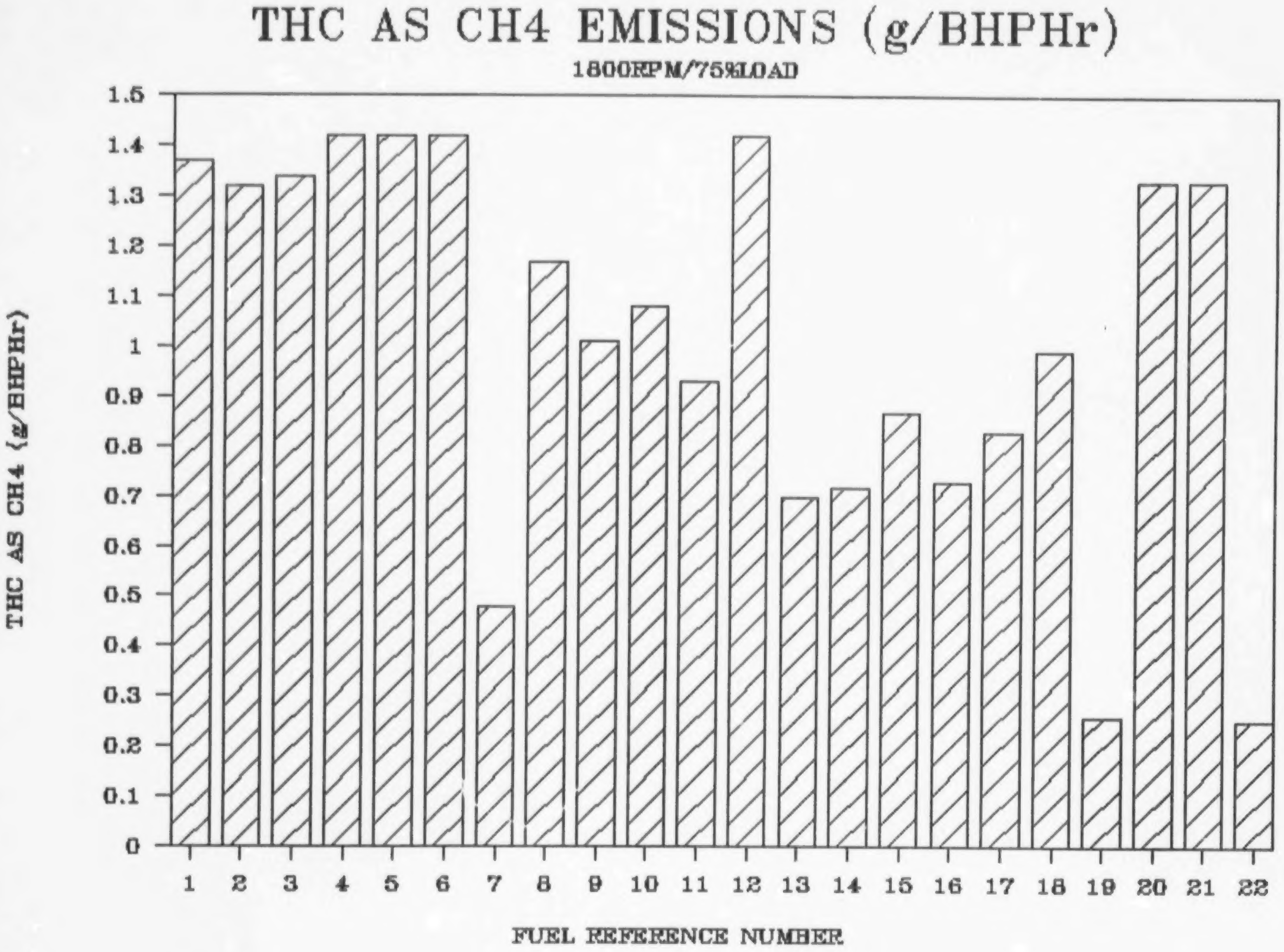
IDLE



THC AS CH4 EMISSIONS (g/BHPHr)

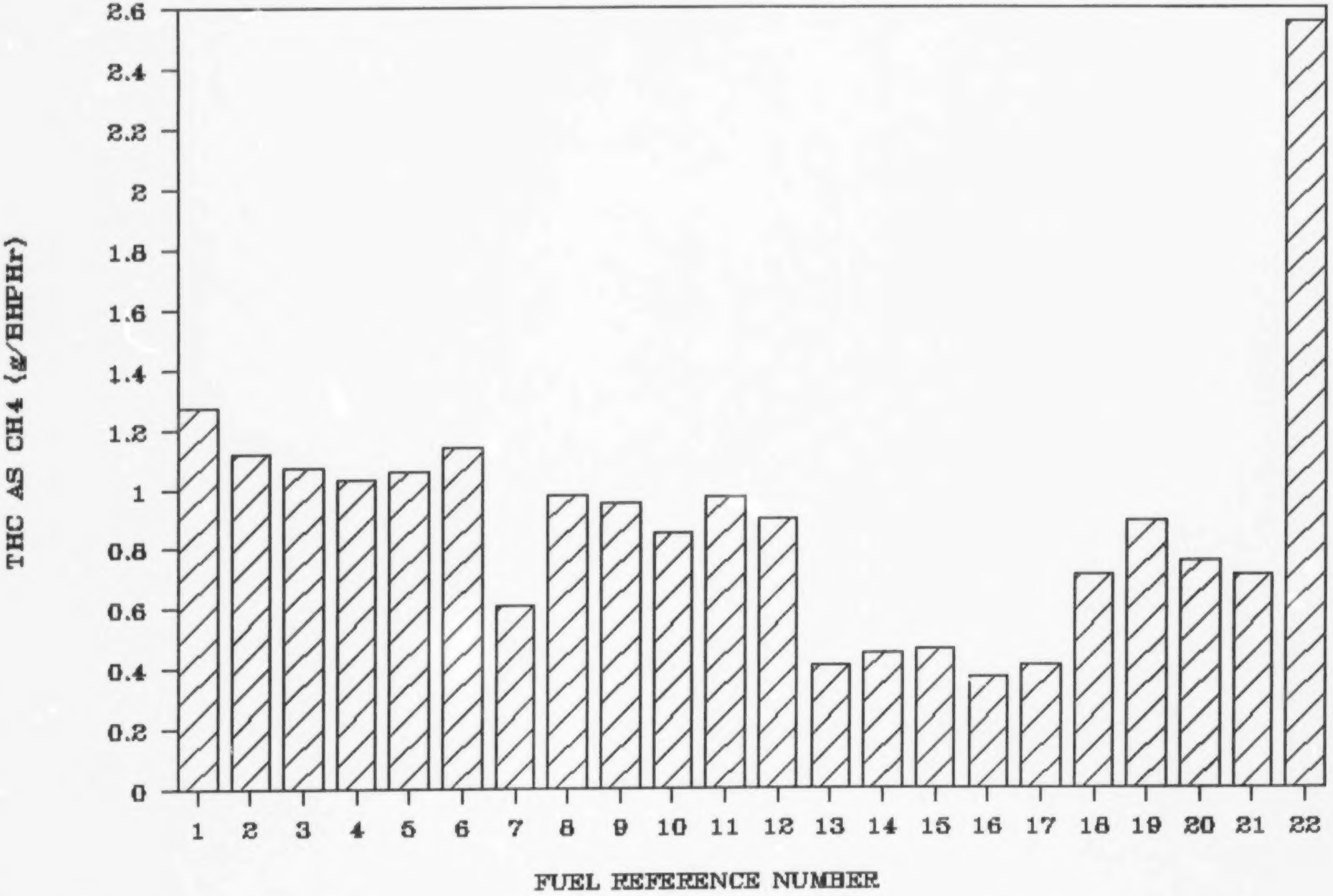
1400RPM/25%LOAD




THC AS CH4 EMISSIONS (g/BHPHr)
1800RPM/75%LOAD
THC AS CH4 (g/BHPHr)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
FUEL REFERENCE NUMBER

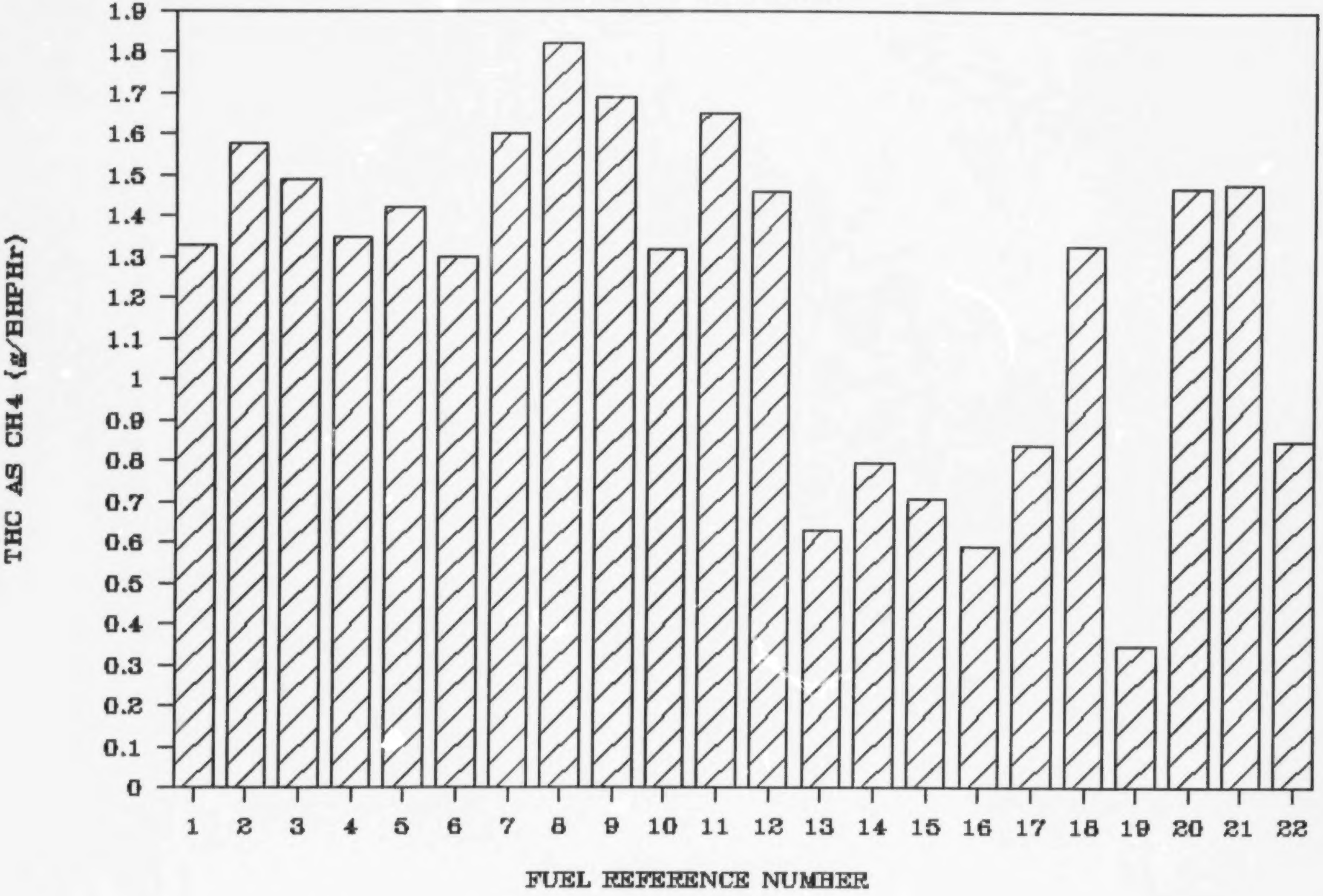
THC AS CH4 EMISSIONS (g/BHPHr)

1600RPM/100%LOAD



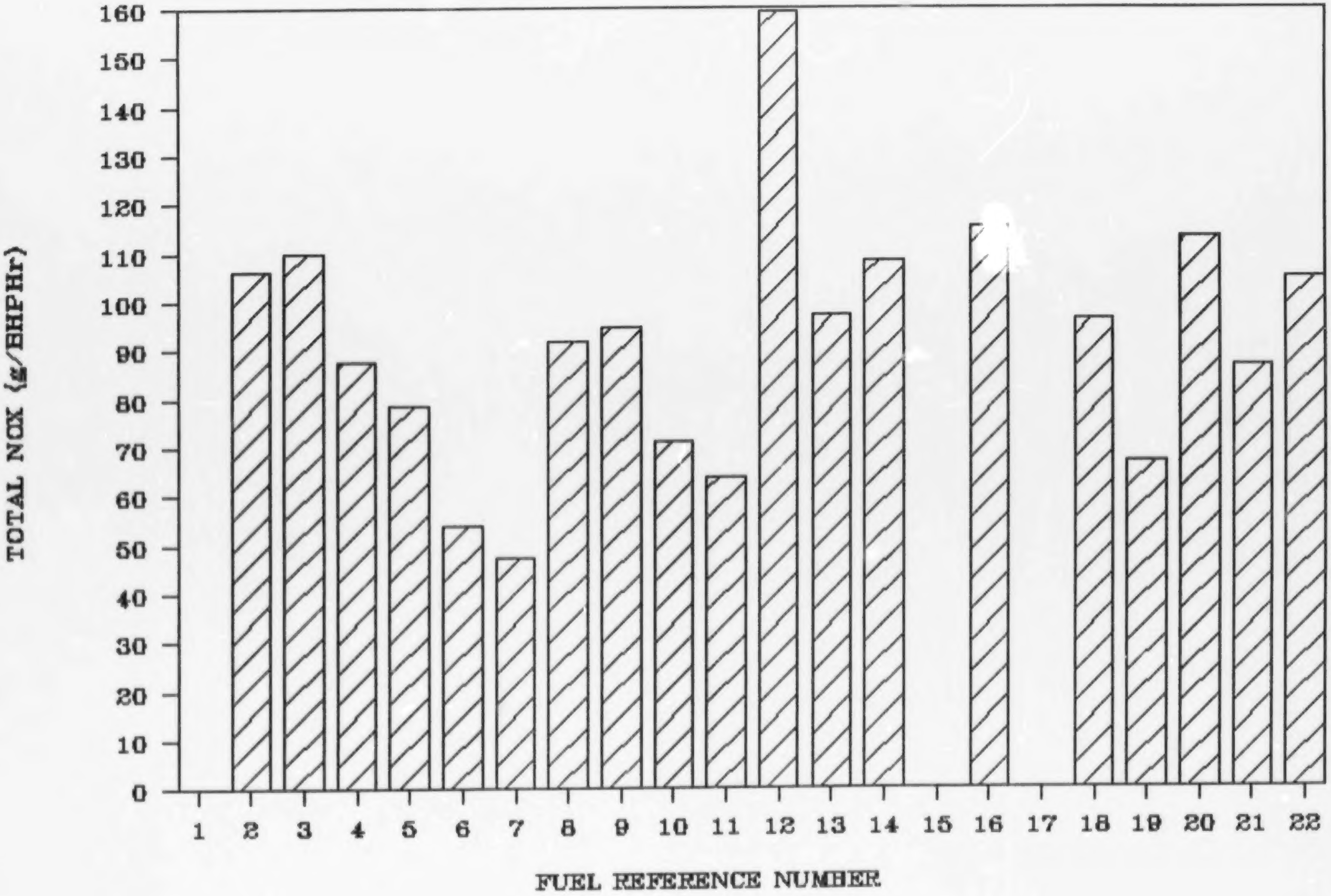
THC AS CH4 EMISSIONS (g/BHPHr)

2200RPM/100%LOAD



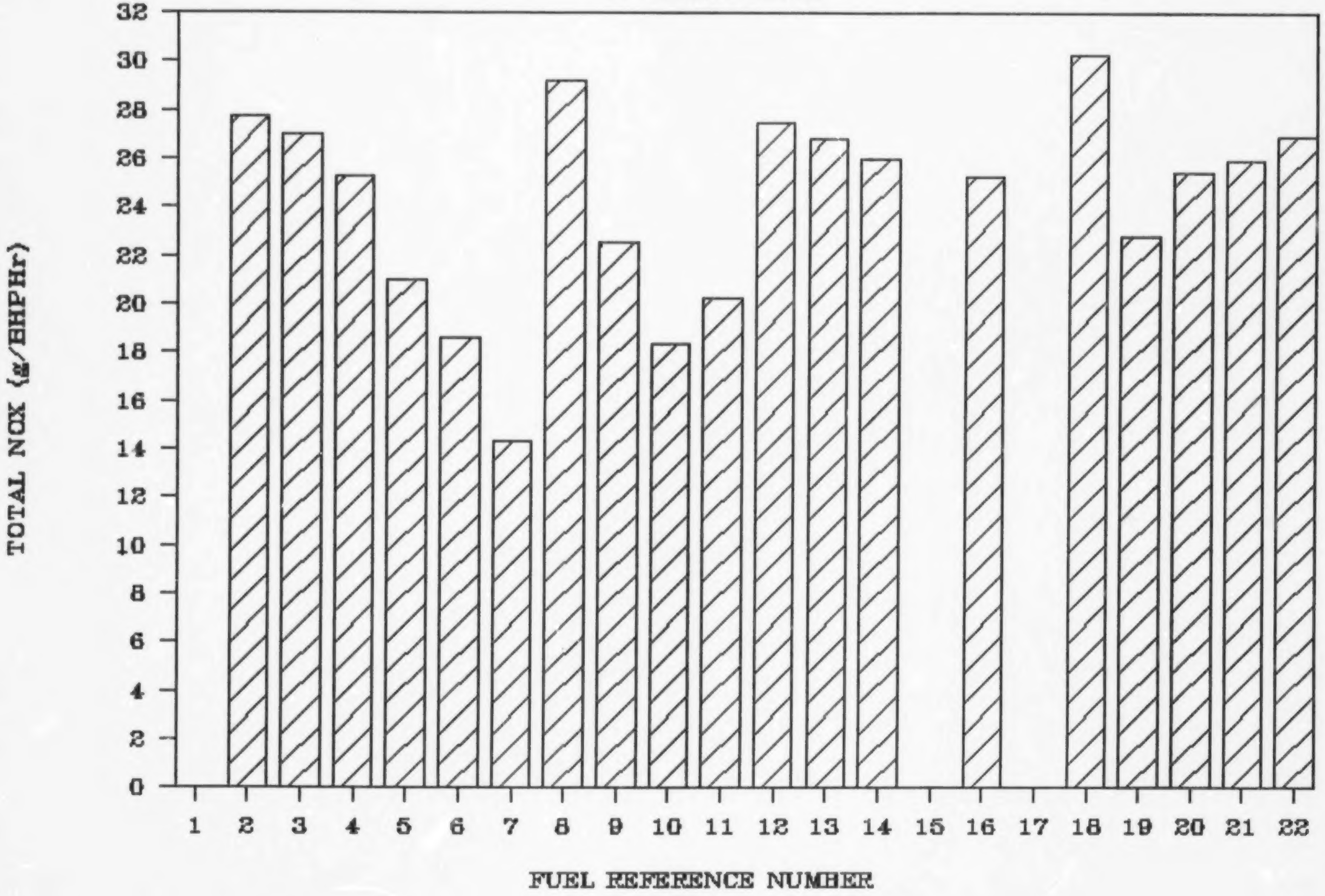
TOTAL NOX EMISSIONS (g/BHPHr)

IDLE



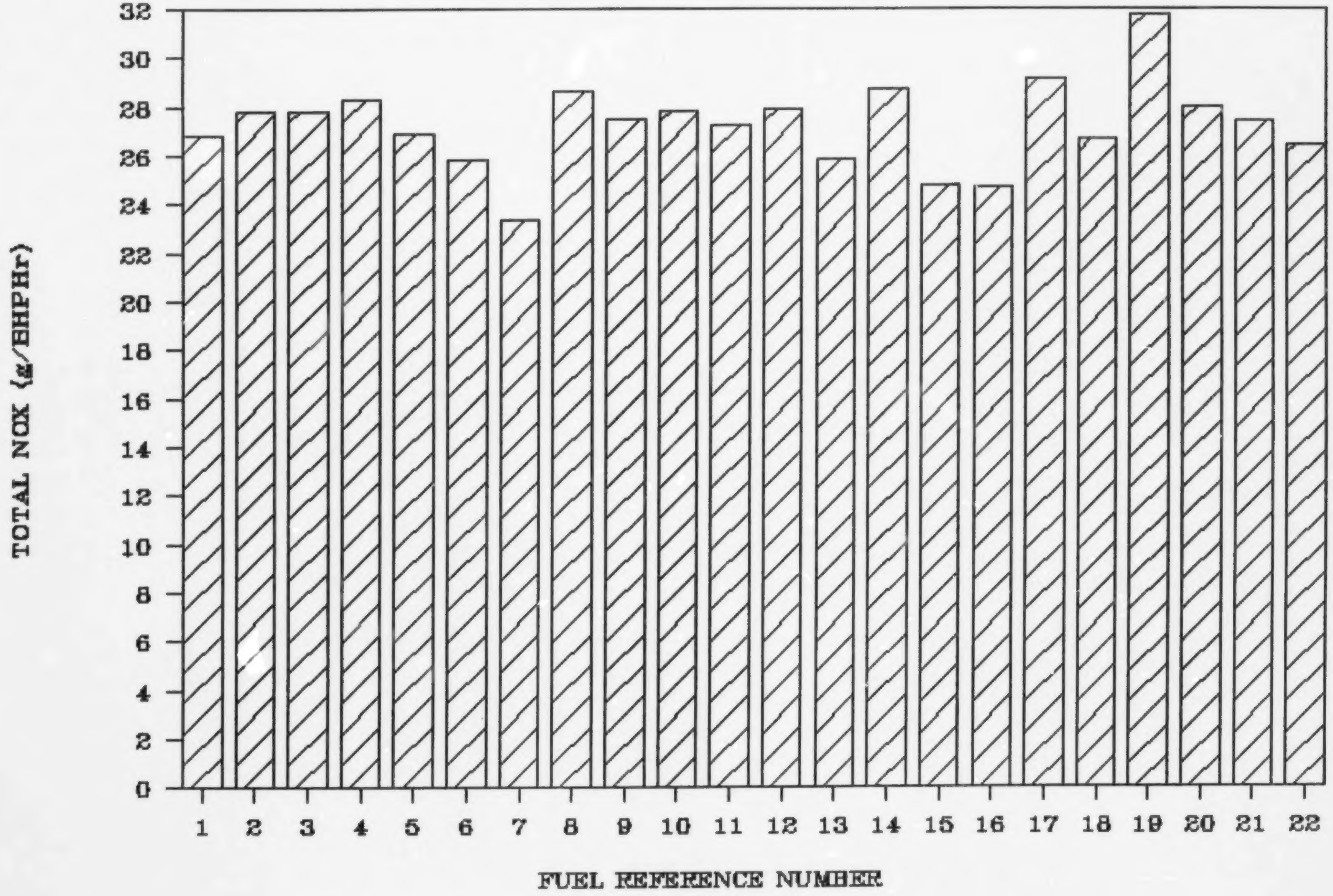
TOTAL NOX EMISSIONS (g/BHPHr)

1400RPM/25%LOAD



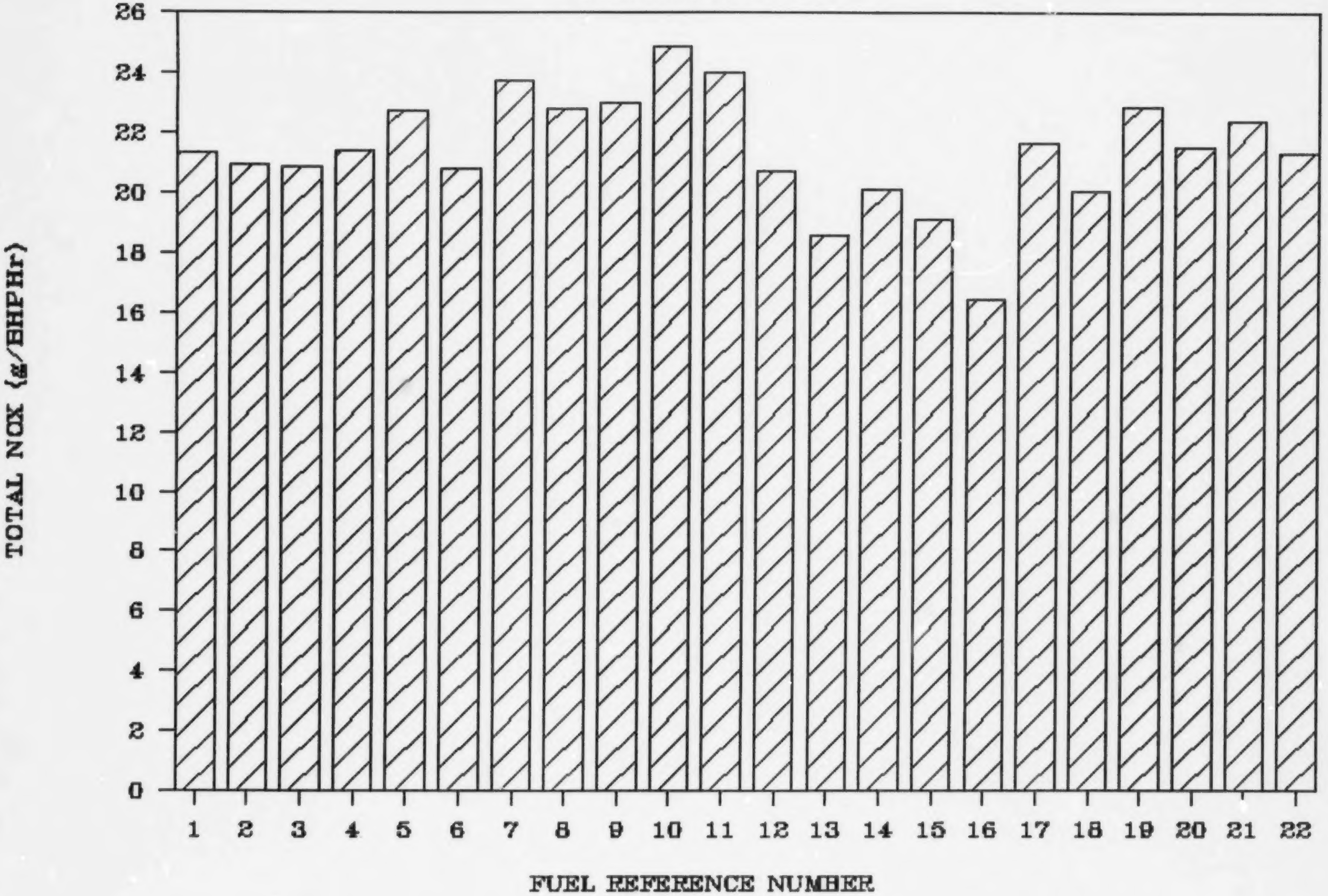
TOTAL NOX EMISSIONS (g/BHPHr)

1800RPM/75%LOAD



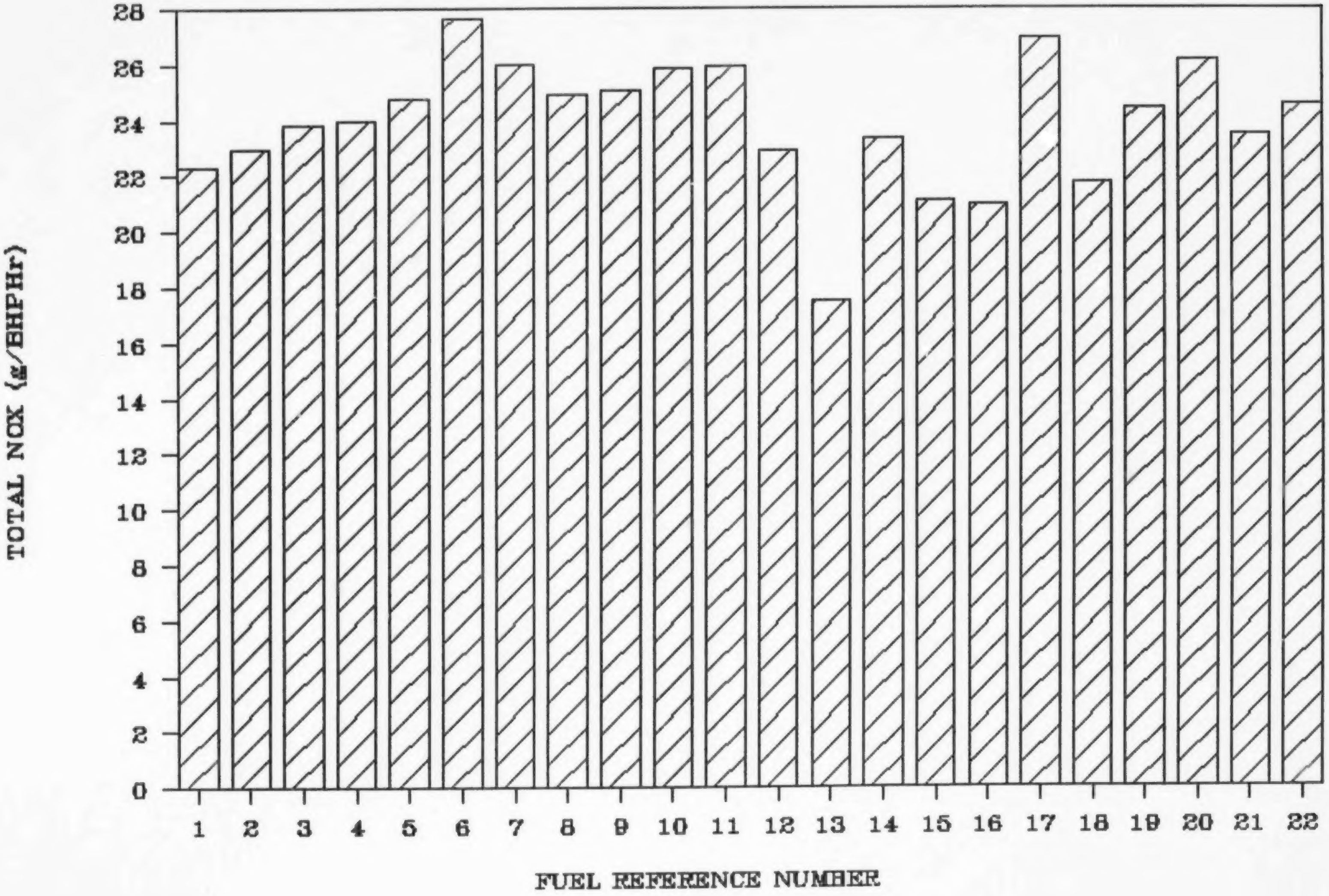
TOTAL NOX EMISSIONS (g/BHPHr)

1600RPM/100%LOAD

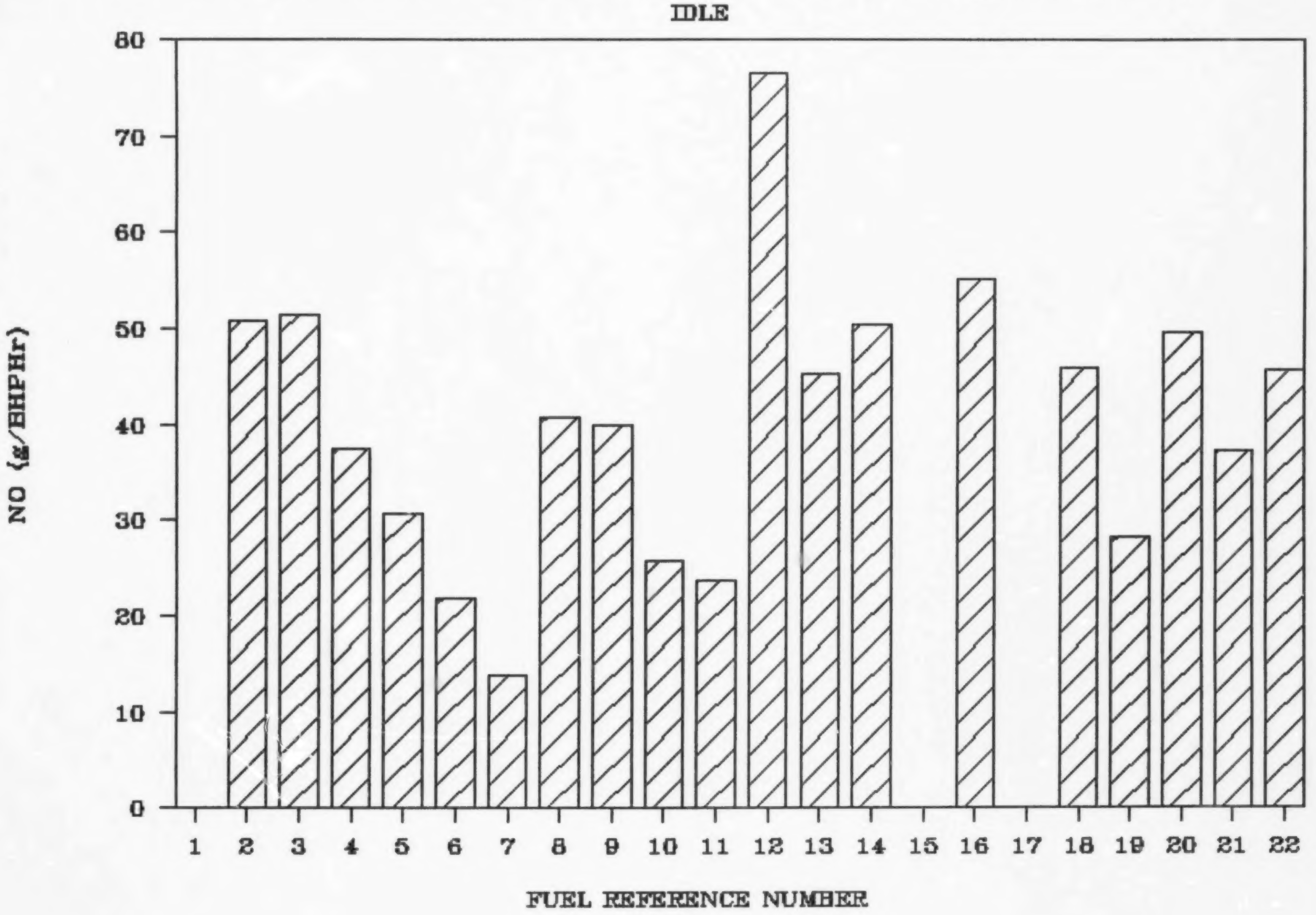


TOTAL NOX EMISSIONS (g/BHPHr)

2200RPM/100%LOAD

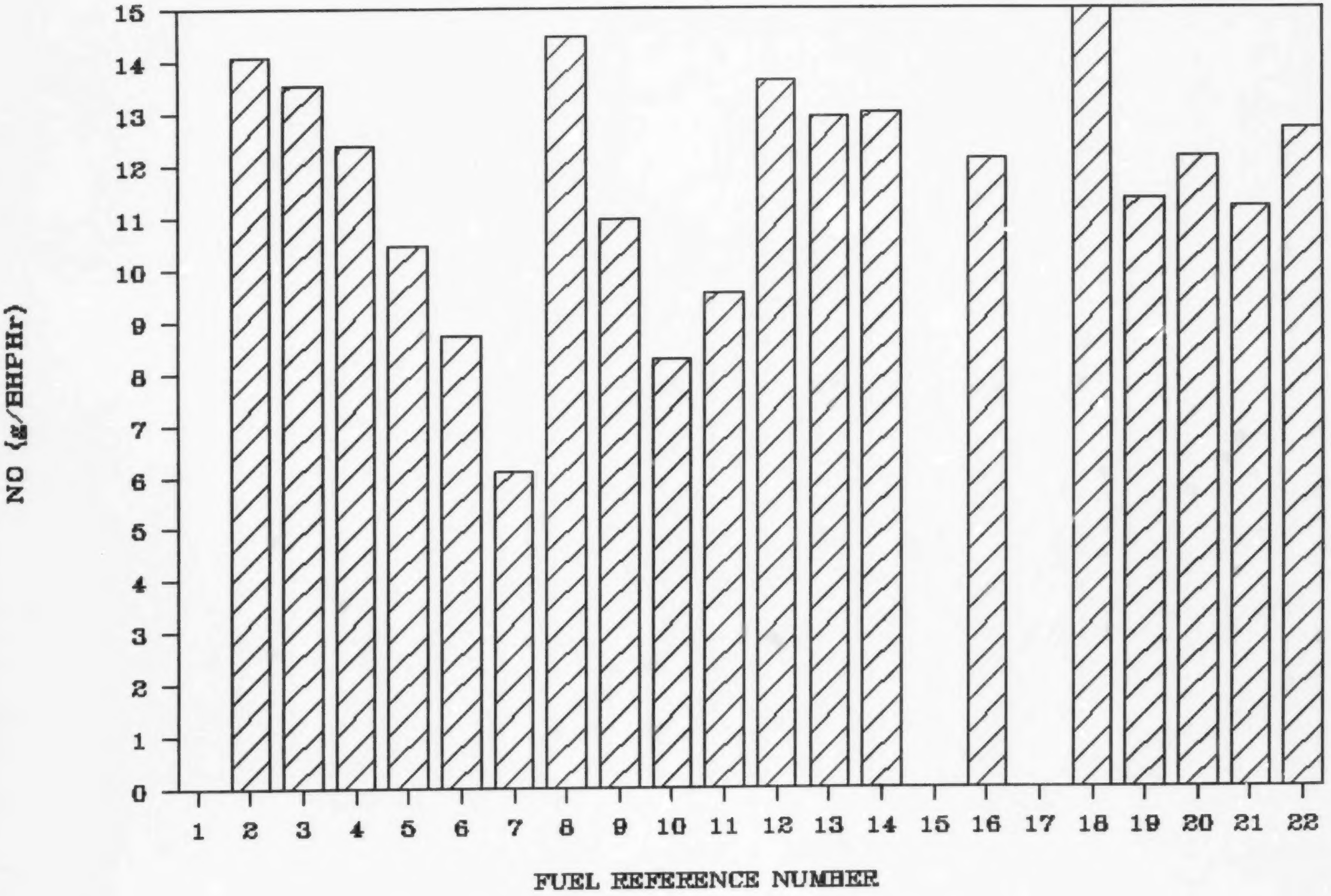


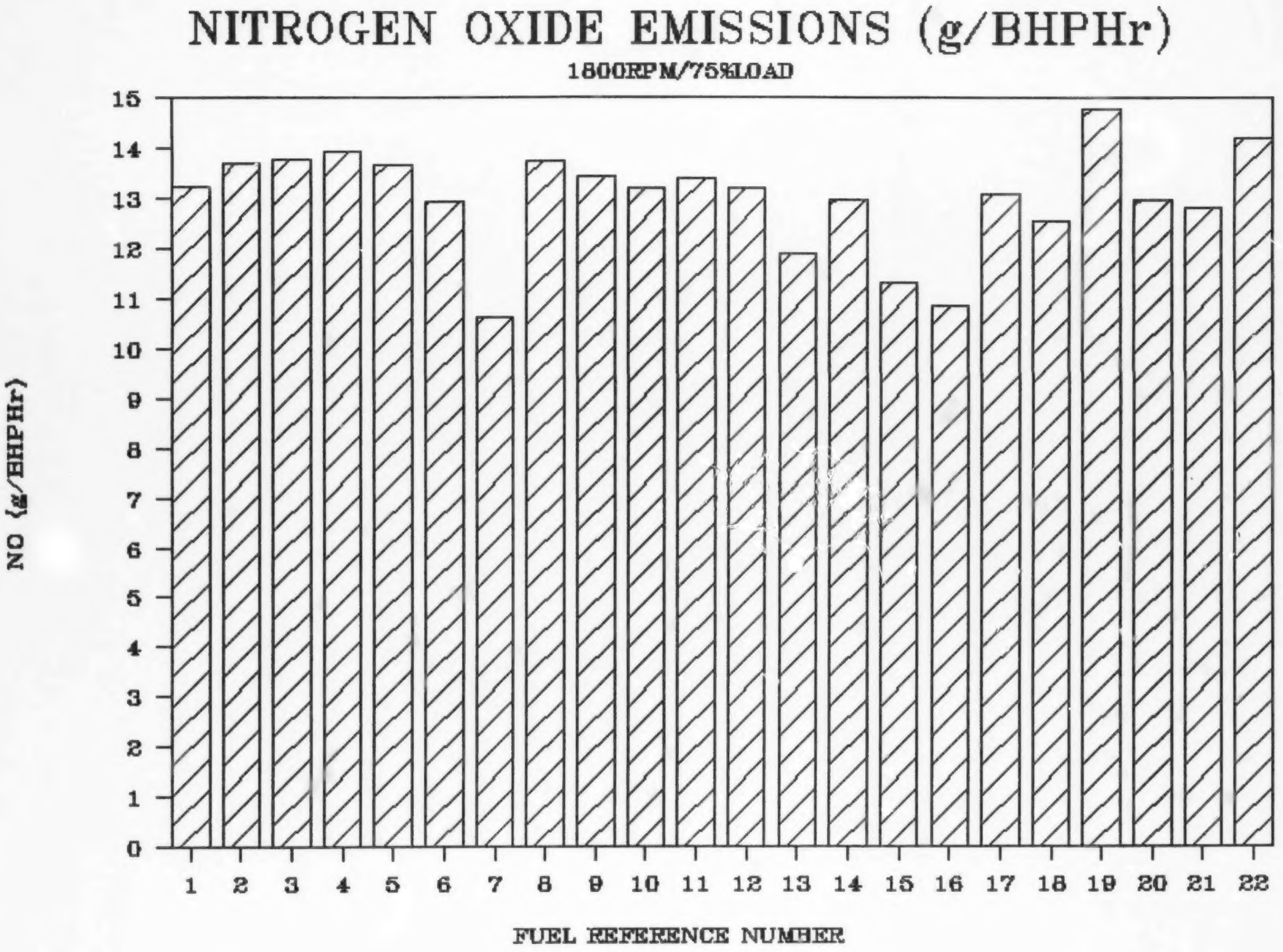
NITROGEN OXIDE EMISSIONS (g/BHPHr)



NITROGEN OXIDE EMISSIONS (g/BHPHr)

1400RPM/25%LOAD




NITROGEN OXIDE EMISSIONS (g/BHPHr)
1800RPM/75%LOAD
NO (g/BHPHr)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1
2
3
4
5
6
7
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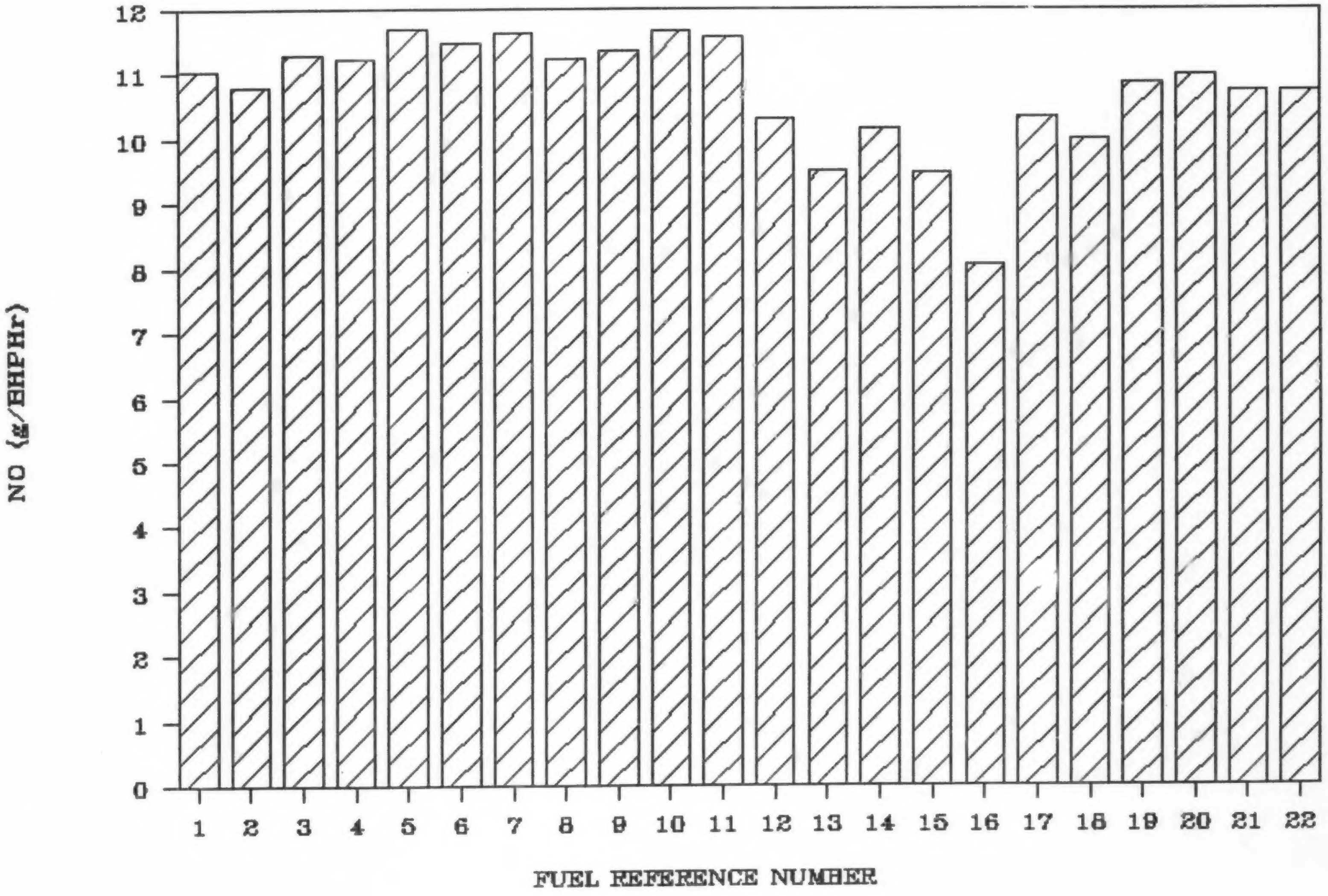
21
22
FUEL REFERENCE NUMBER

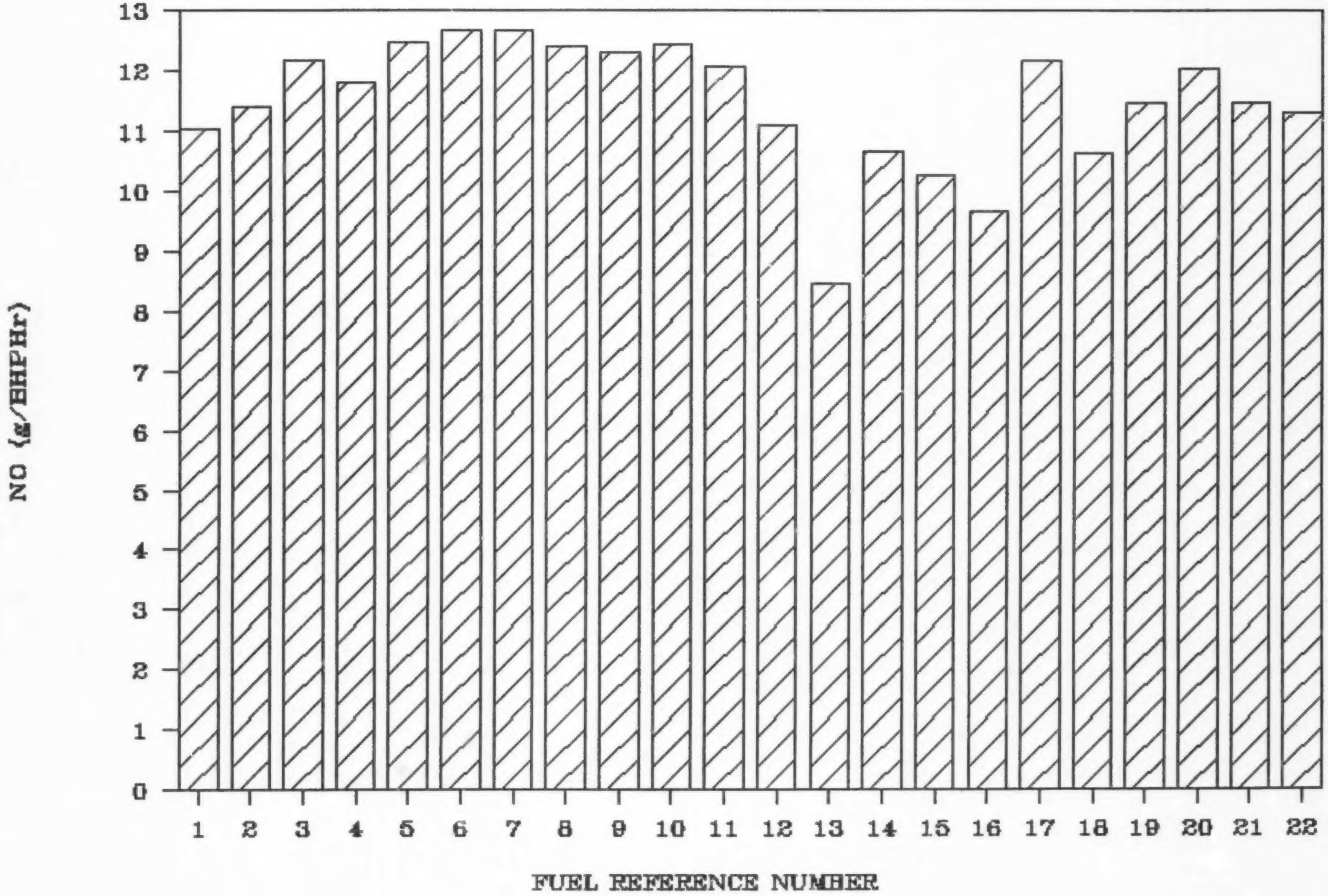
NITROGEN OXIDE EMISSIONS (g/BHPHr)

1600RPM/100%LOAD



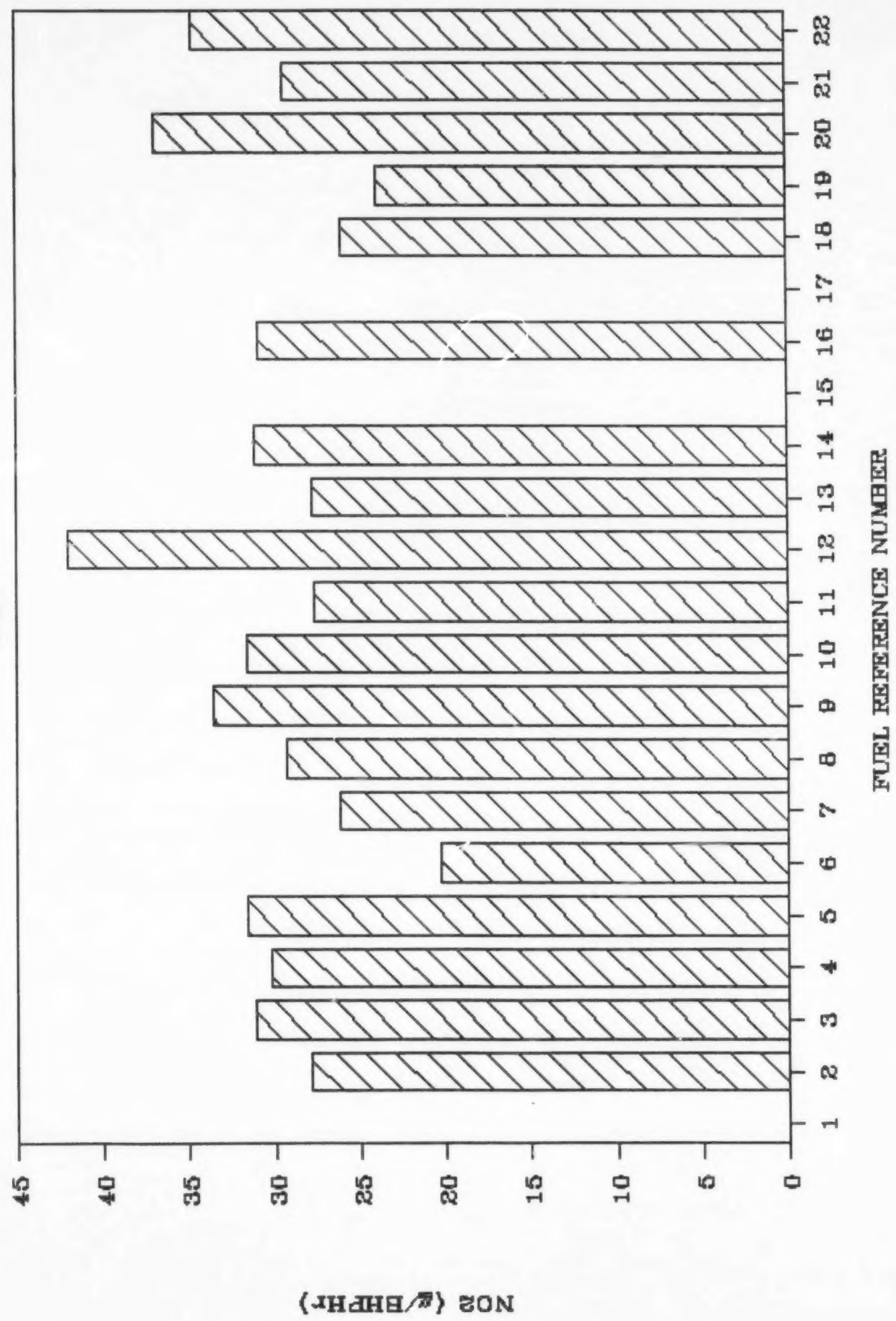
NITROGEN OXIDE EMISSIONS (g/BHPHr)

2200RPM/100%LOAD



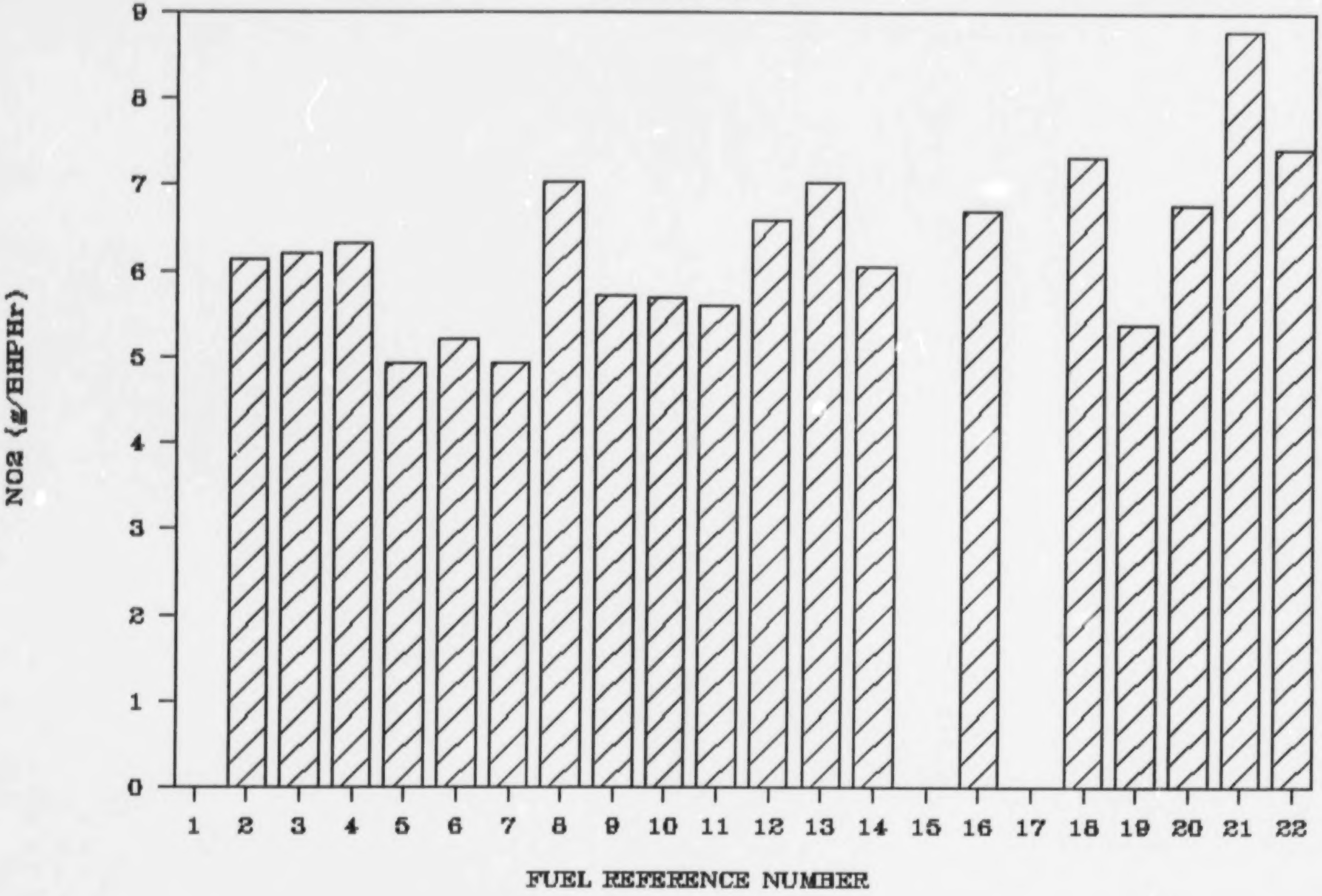
NITROGEN DIOXIDE EMISSIONS (g/BHPHr)

IDLE



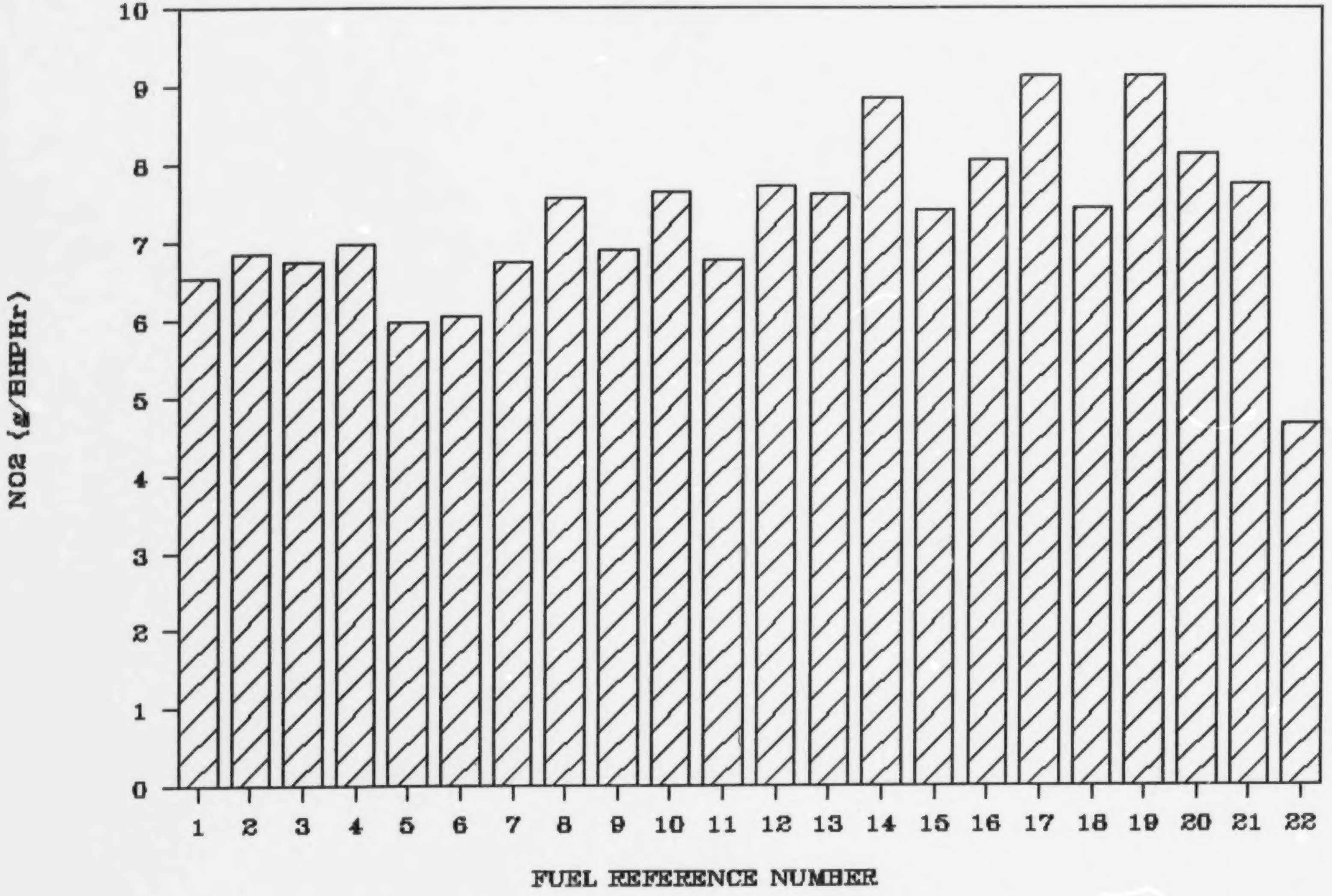
NITROGEN DIOXIDE EMISSIONS (g/BHPHr)

1400RPM/25%LOAD



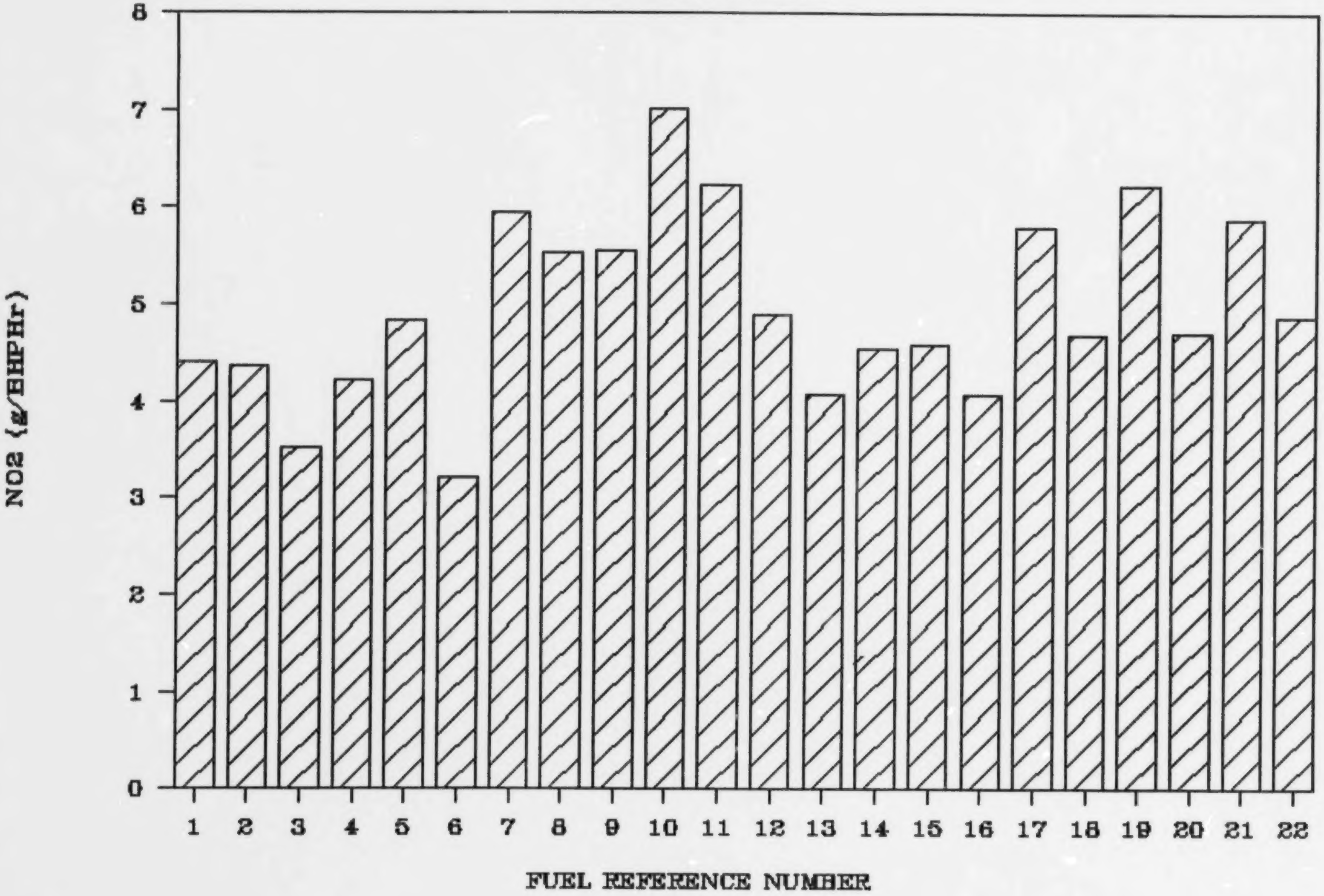
NITROGEN DIOXIDE EMISSIONS (g/BHPHr)

1800RPM/75%LOAD



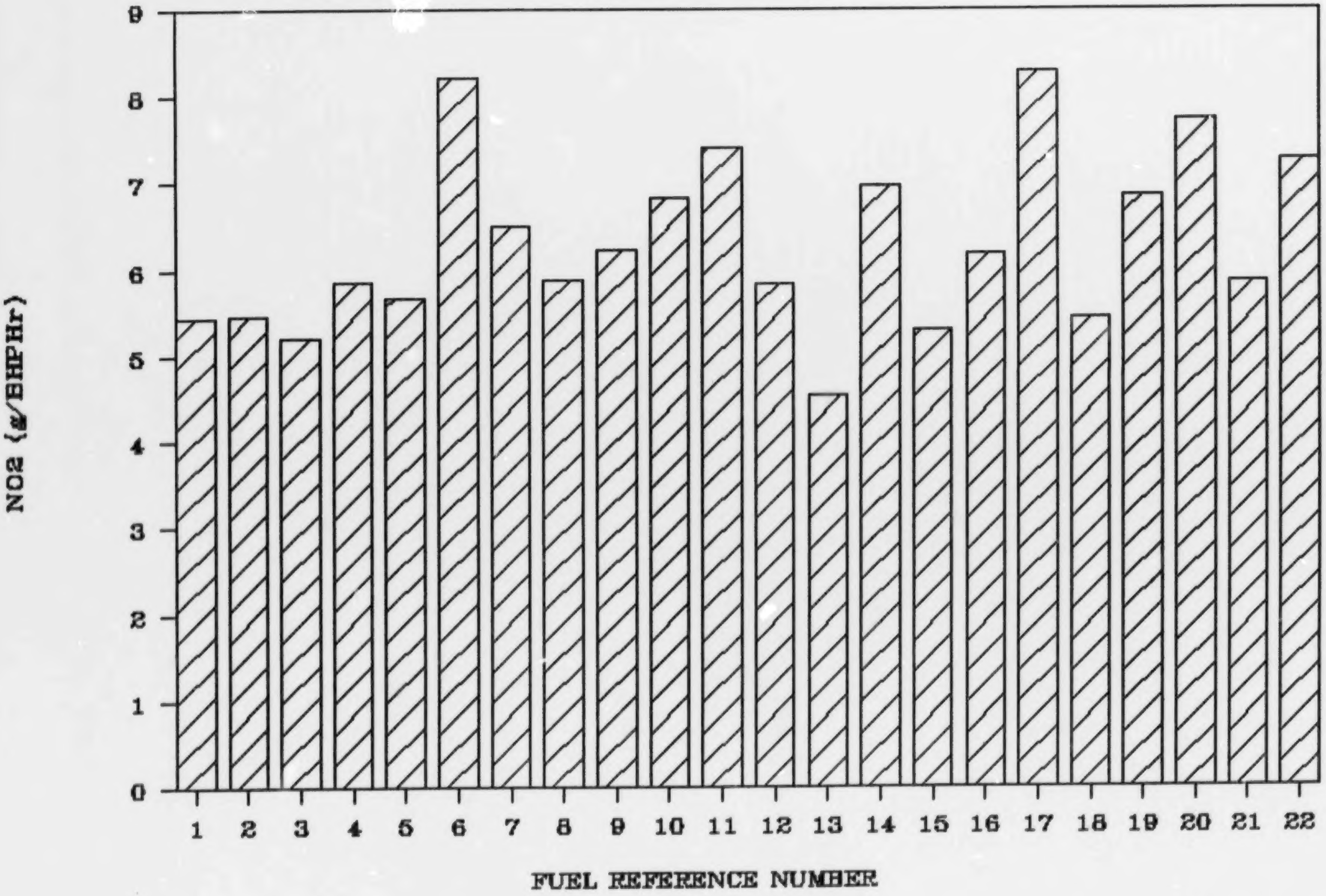
NITROGEN DIOXIDE EMISSIONS (g/BHPHr)

1600RPM/100%LOAD



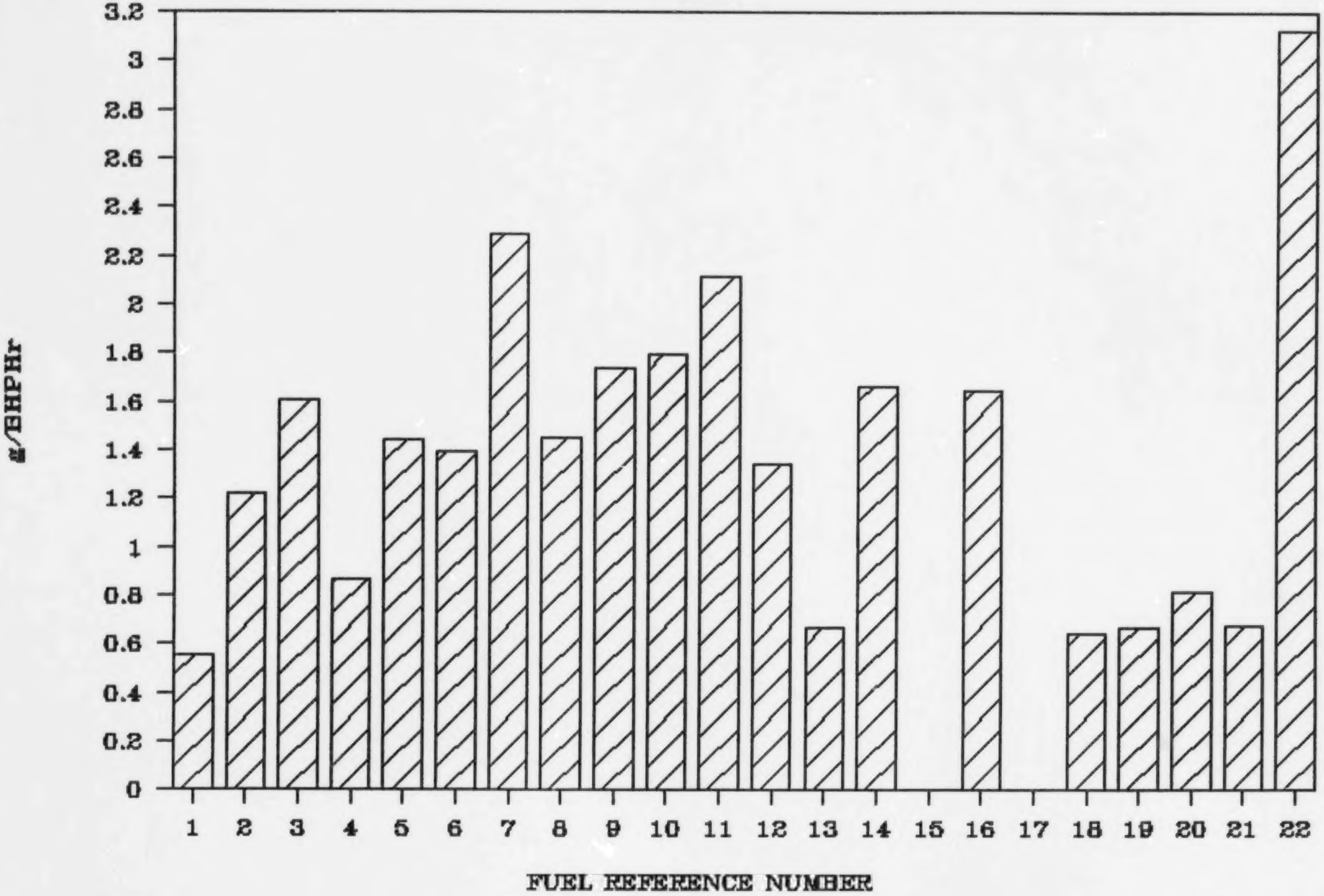
NITROGEN DIOXIDE EMISSIONS (g/BHPHr)

2200RPM/100%LOAD



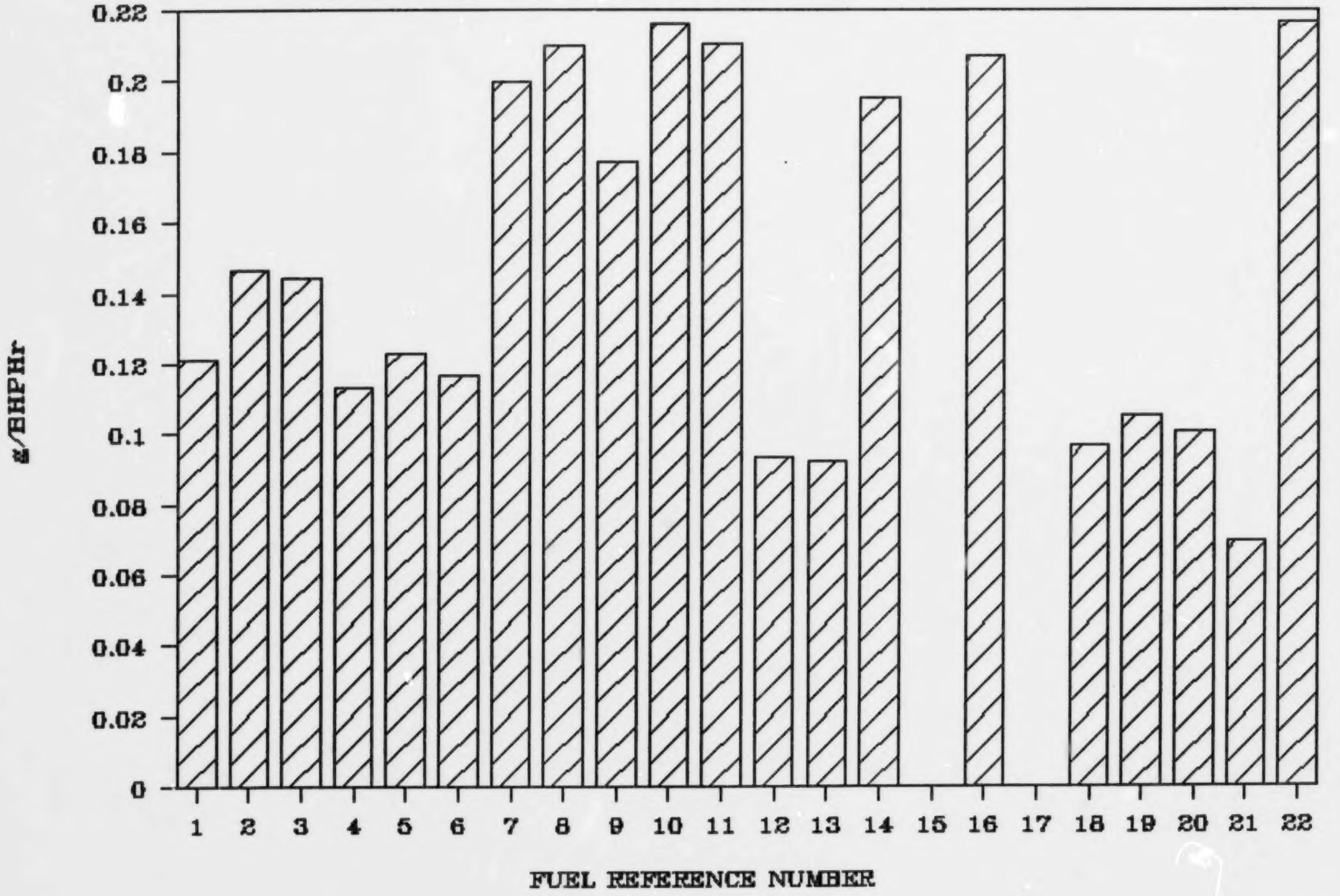
TOTAL PARTICULATES (g/BHPHr)

IDLE



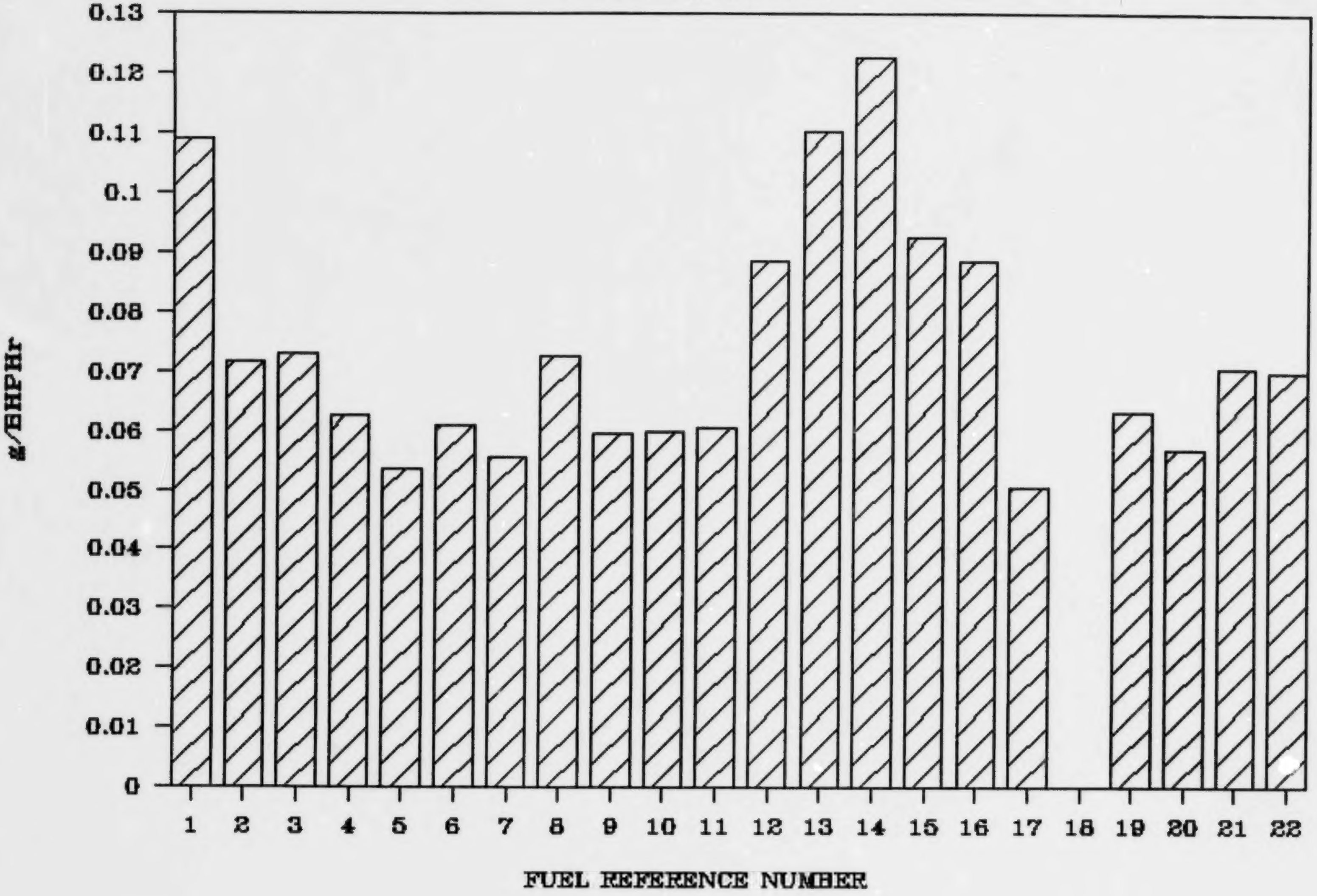
TOTAL PARTICULATES (g/BHPHr)

1400RPM/25%LOAD



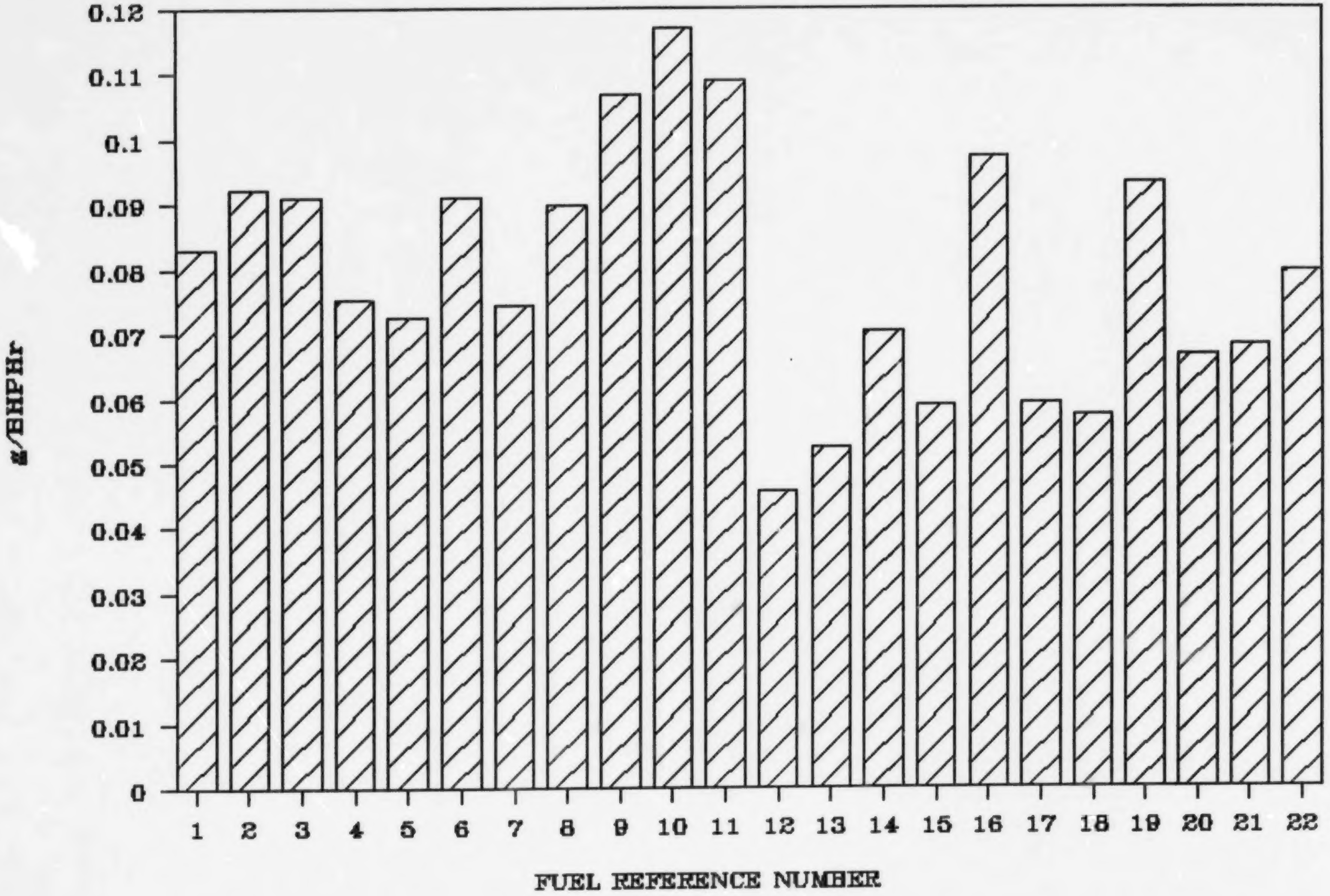
TOTAL PARTICULATES (g/BHPHr)

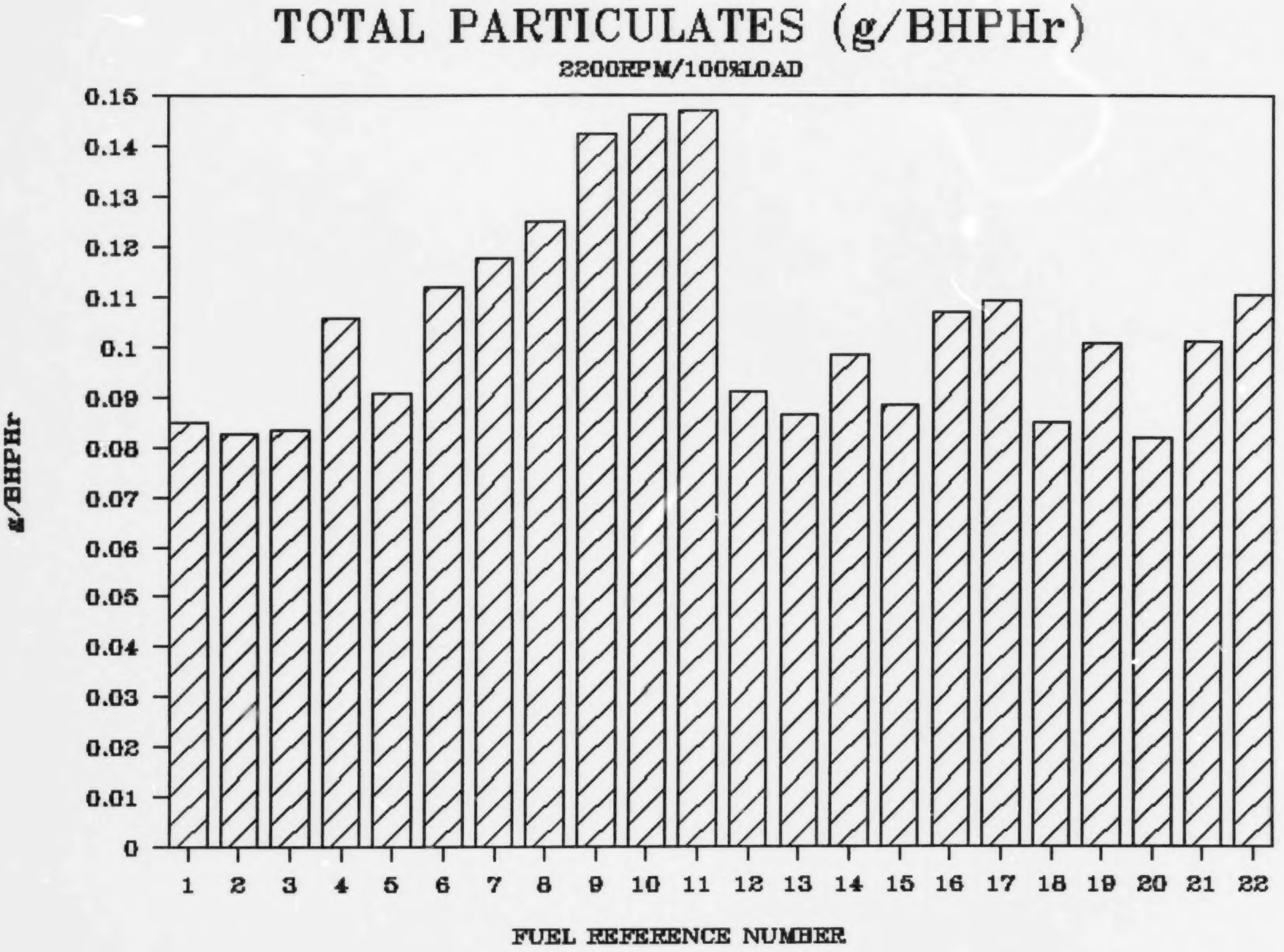
1600RPM/100%LOAD



TOTAL PARTICULATES (g/BHPHr)

1800RPM/75%LOAD




TOTAL PARTICULATES (g/BHPHr)
2200RPM/100%LOAD
g/BHPHr
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1
2
3
4
5
6
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10
11
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16
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18
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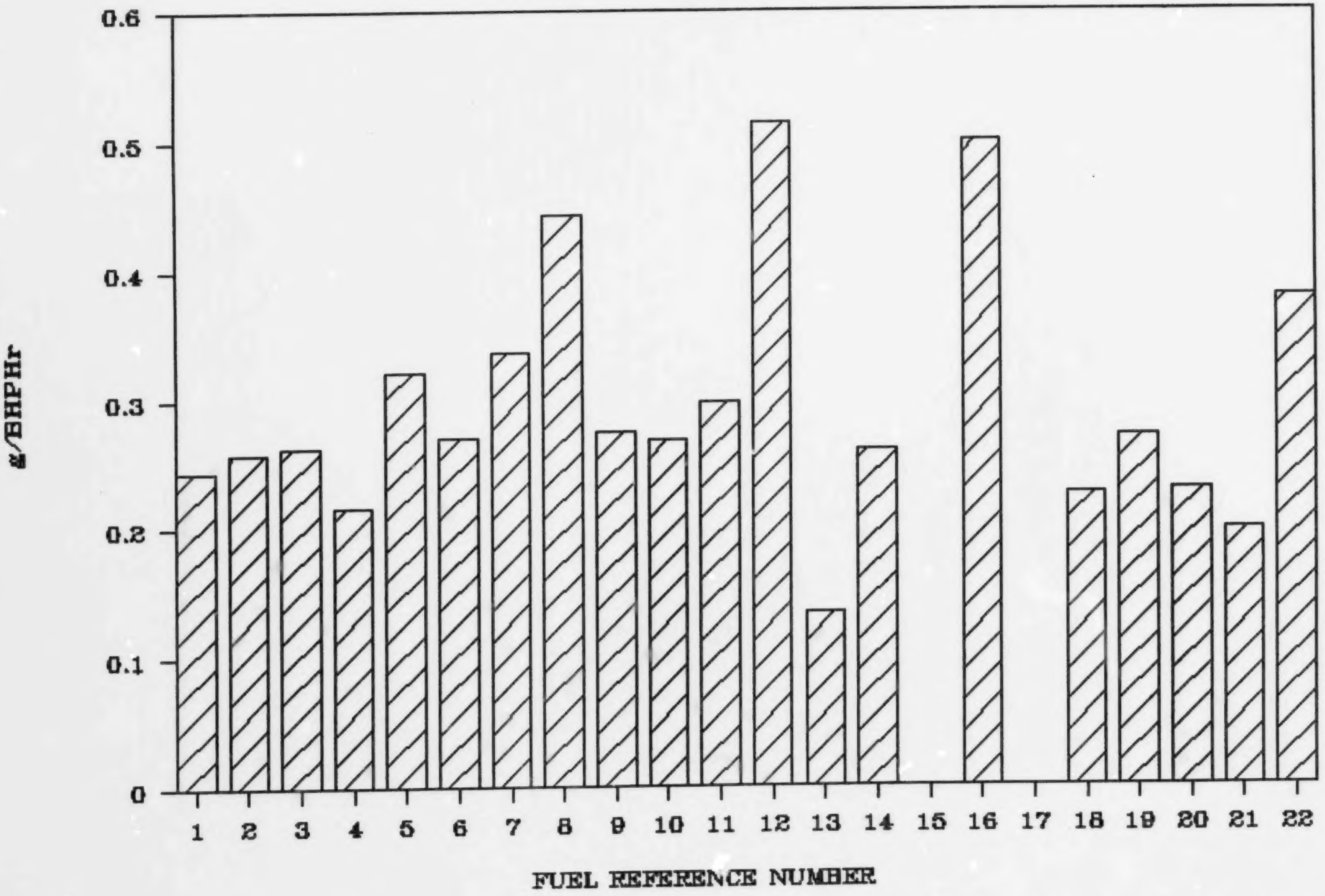
20
21
22
FUEL REFERENCE NUMBER

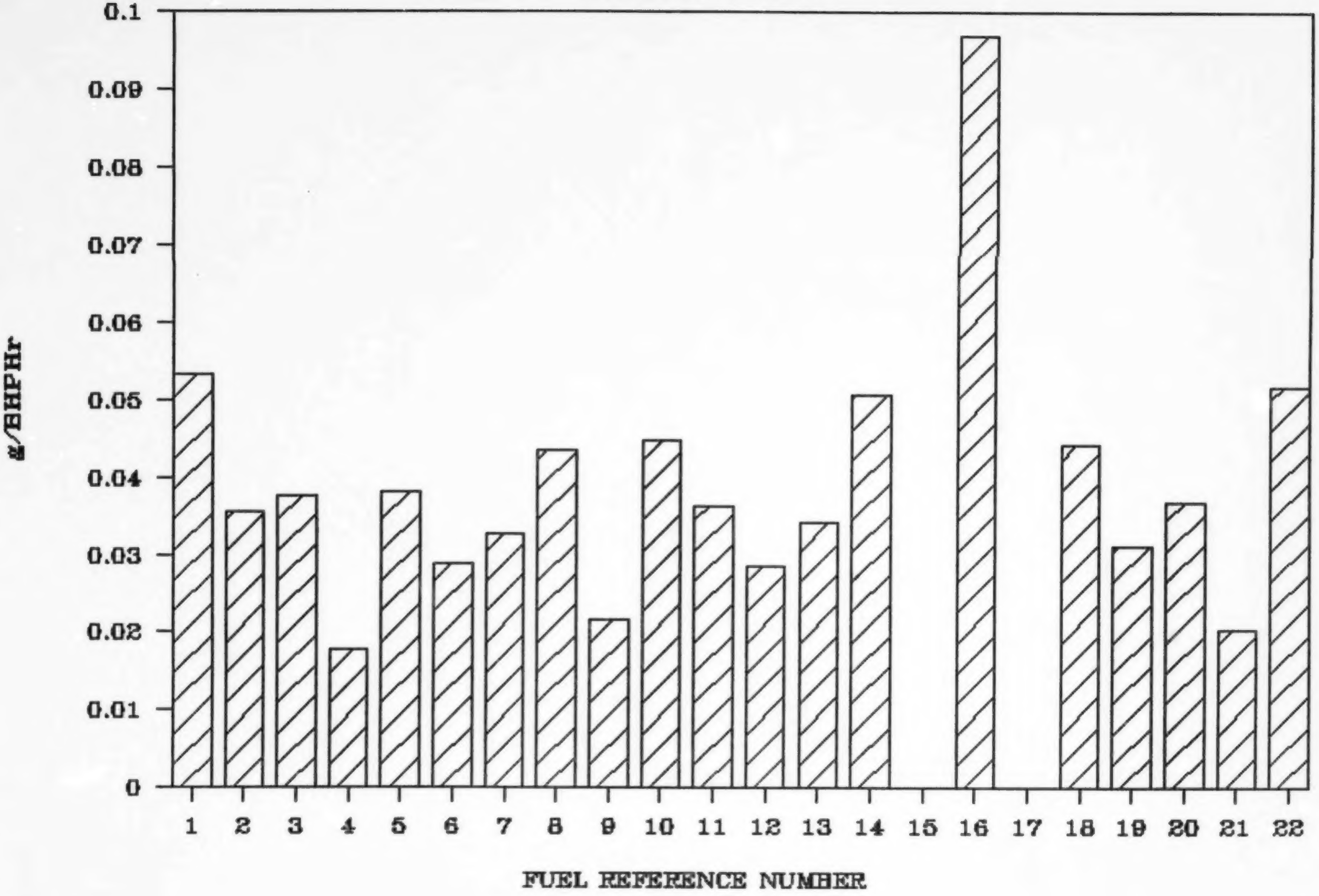
INSOLUBLE PARTICULATES (g/BHPHr)

IDLE



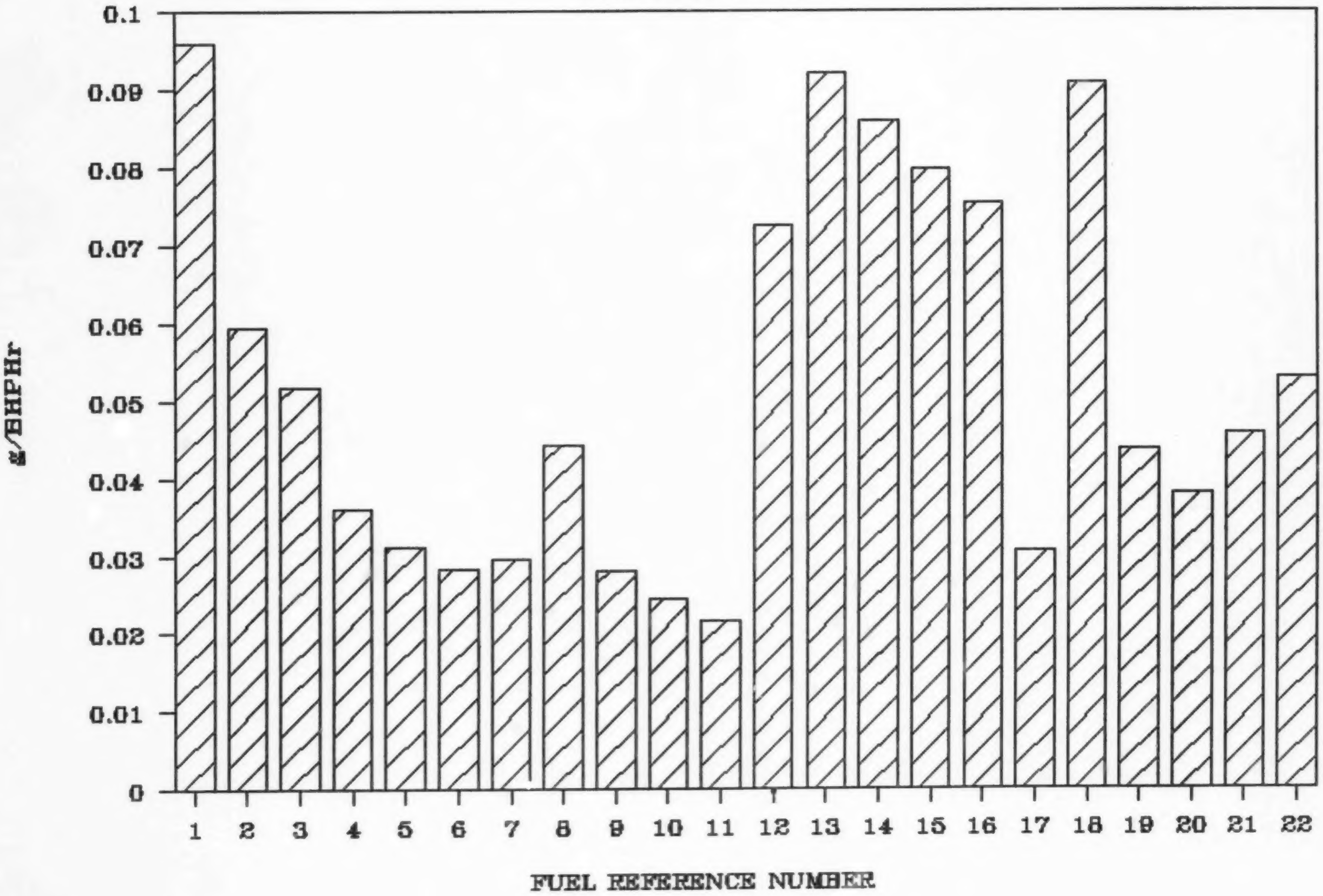
INSOLUBLE PARTICULATES (g/BHPHr)

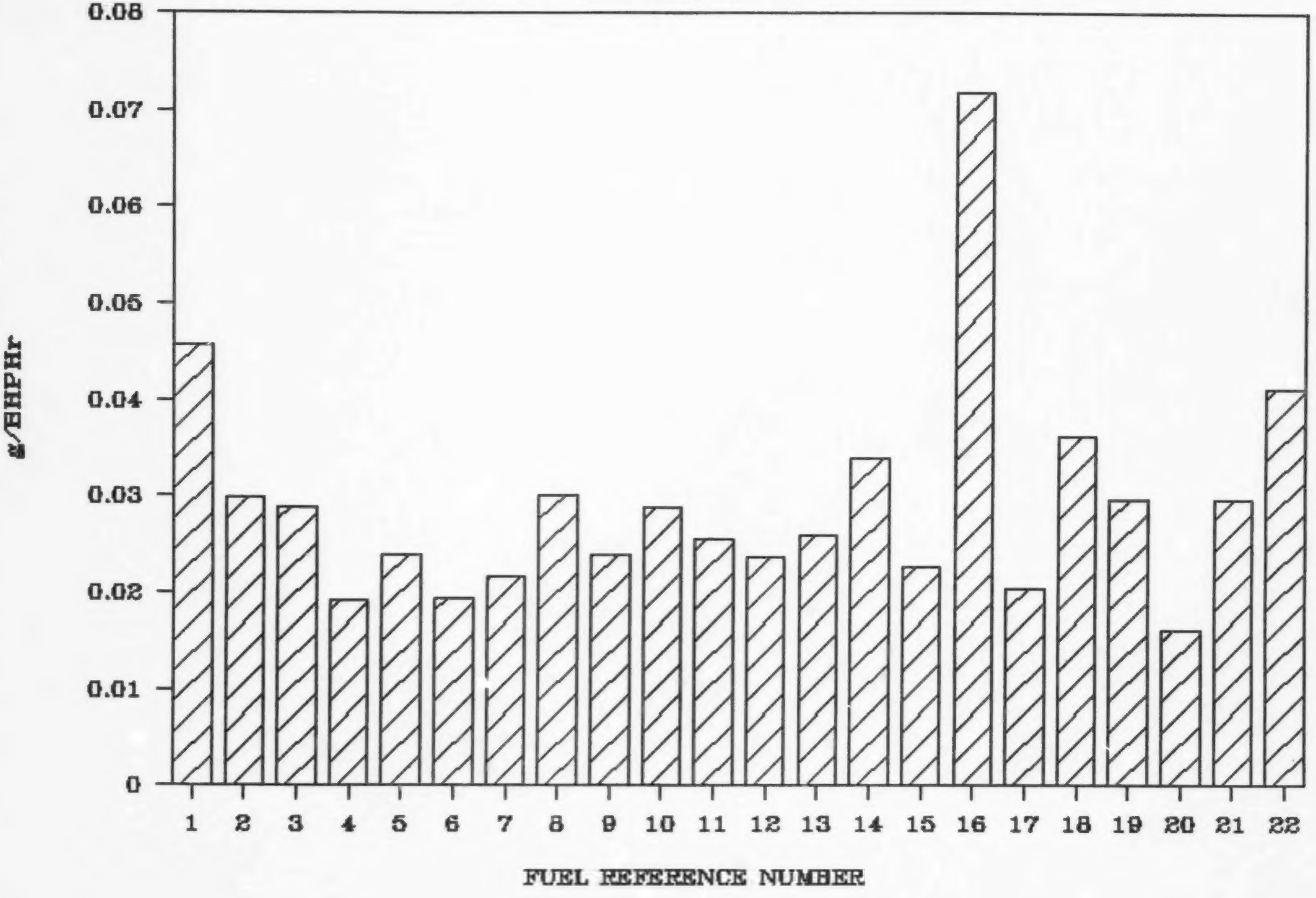
1400RPM/25%LOAD



INSOLUBLE PARTICULATES (g/BHPHr)

1600RPM/100%LOAD



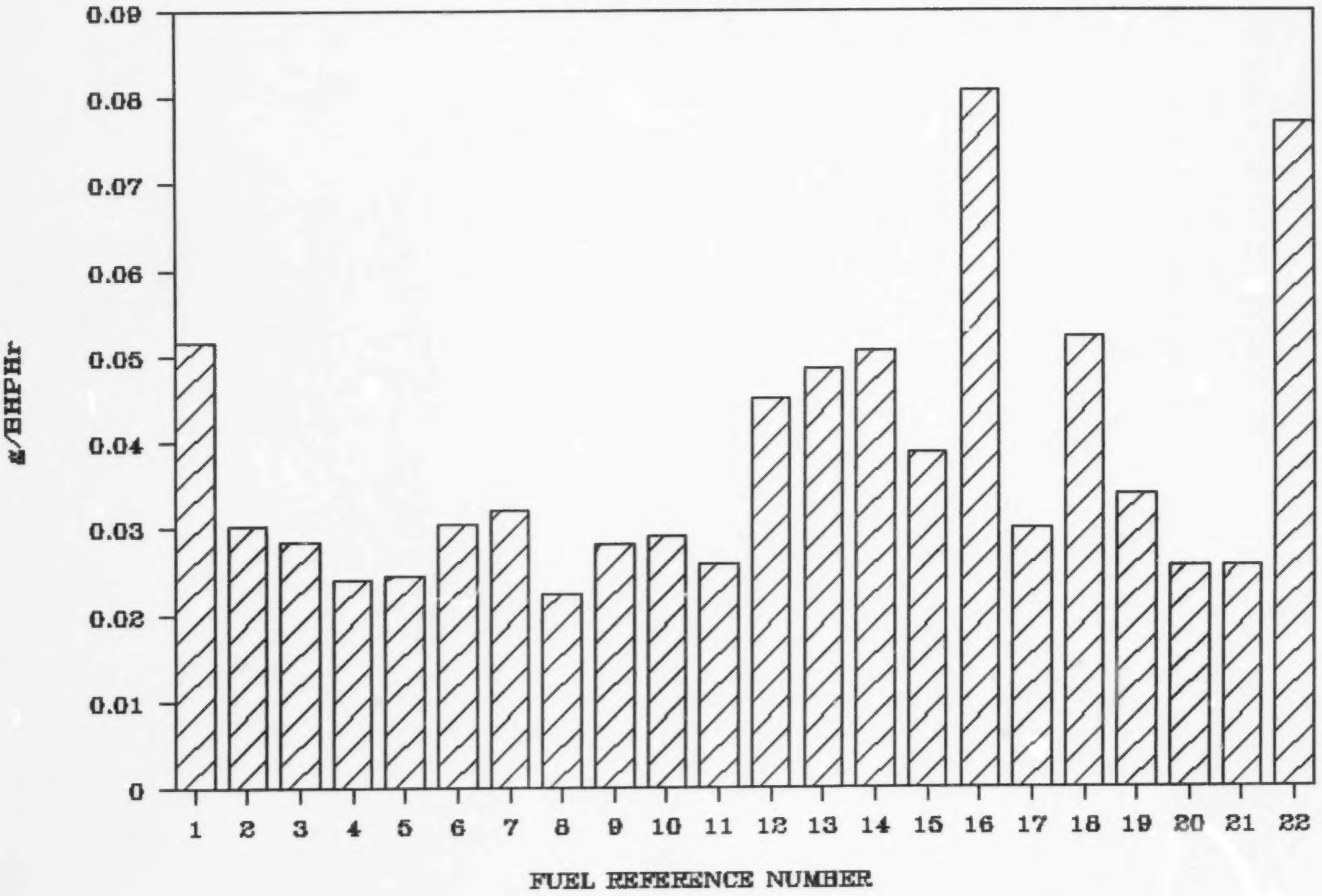


INSOLUBLE PARTICULATES (g/BHPHr)

1800RPM/75%LOAD

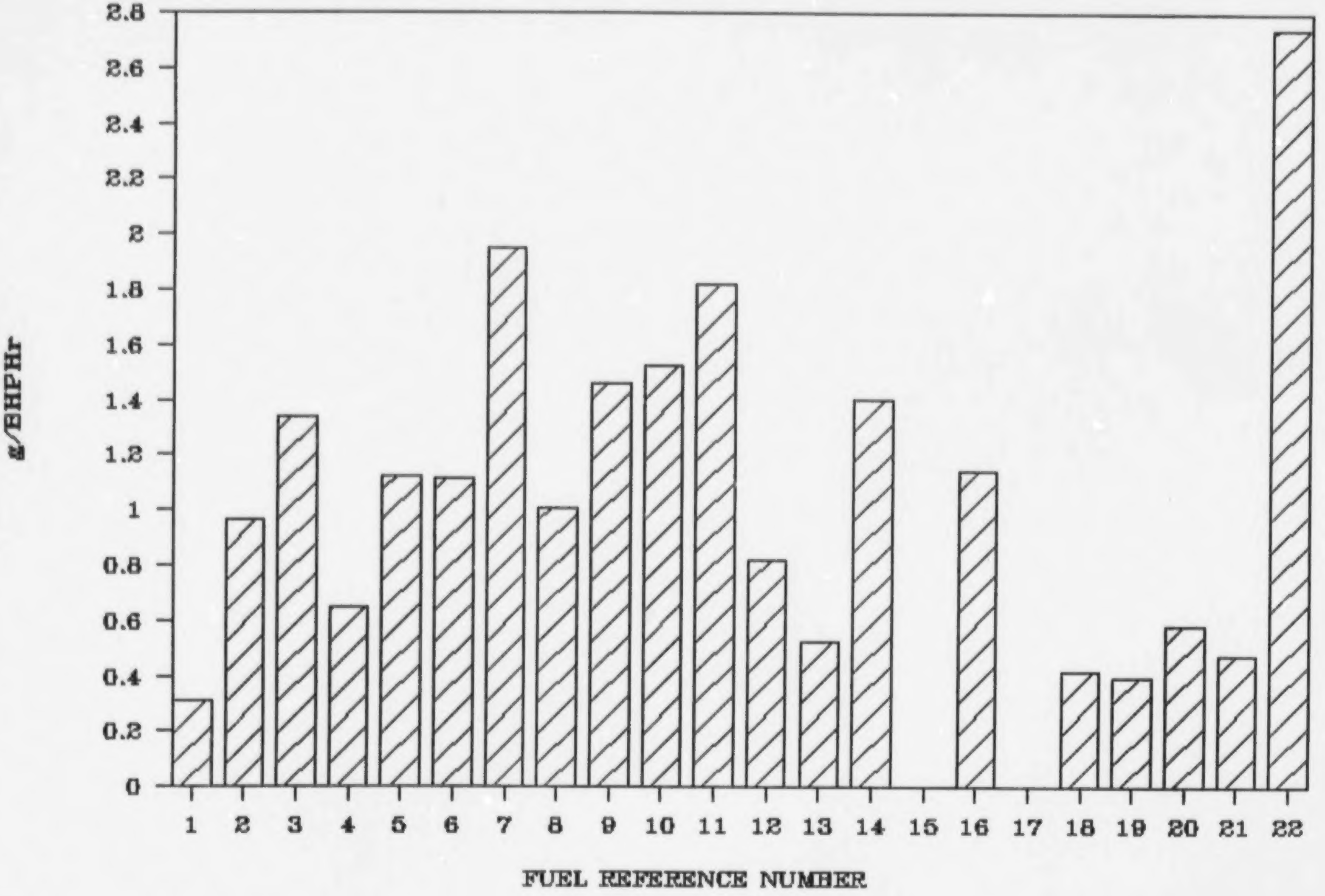
INSOLUBLE PARTICULATES (g/BHPHr)

2200RPM/100%LOAD



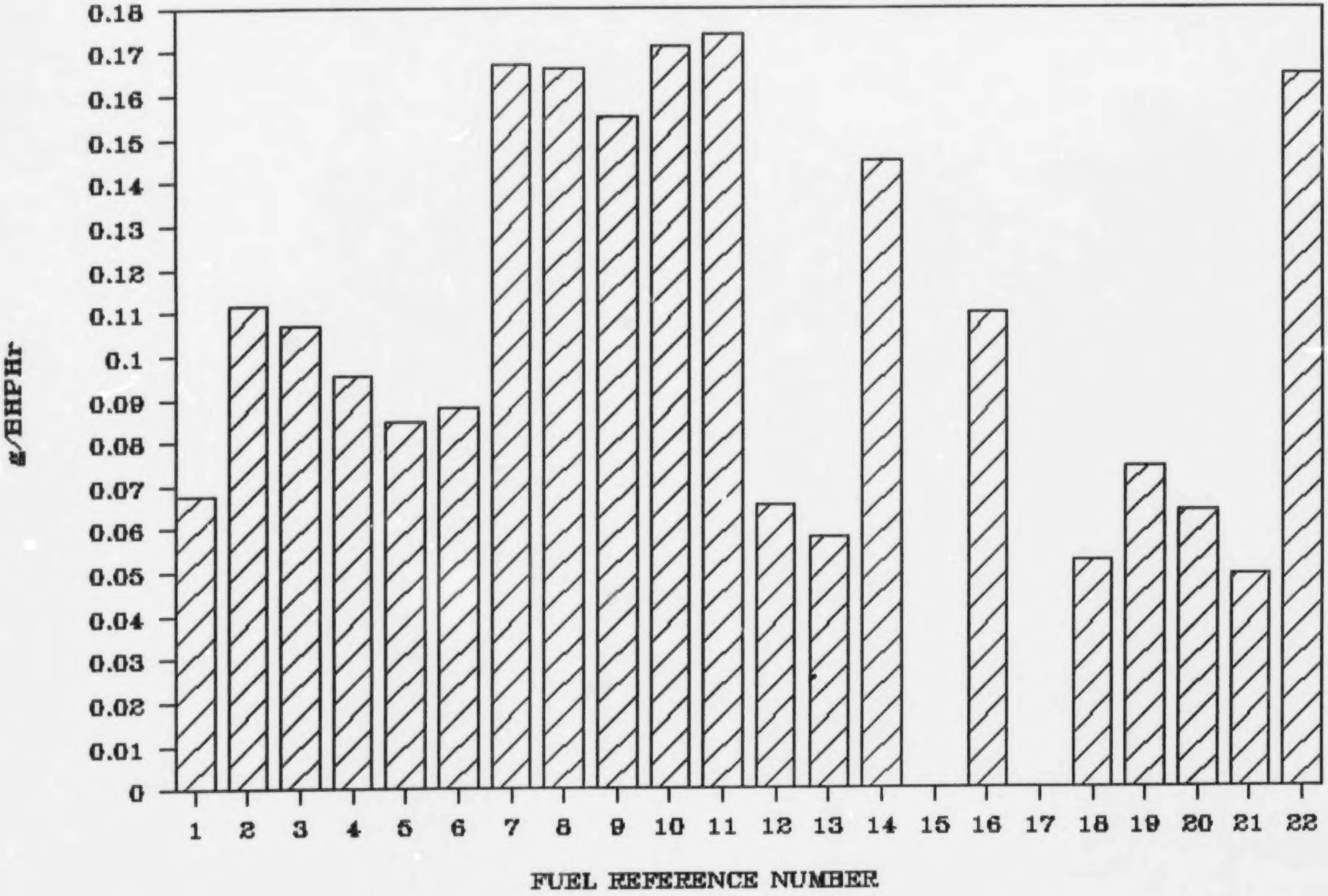
SOLUBLE PARTICULATES (g/BHPHr)

IDLE



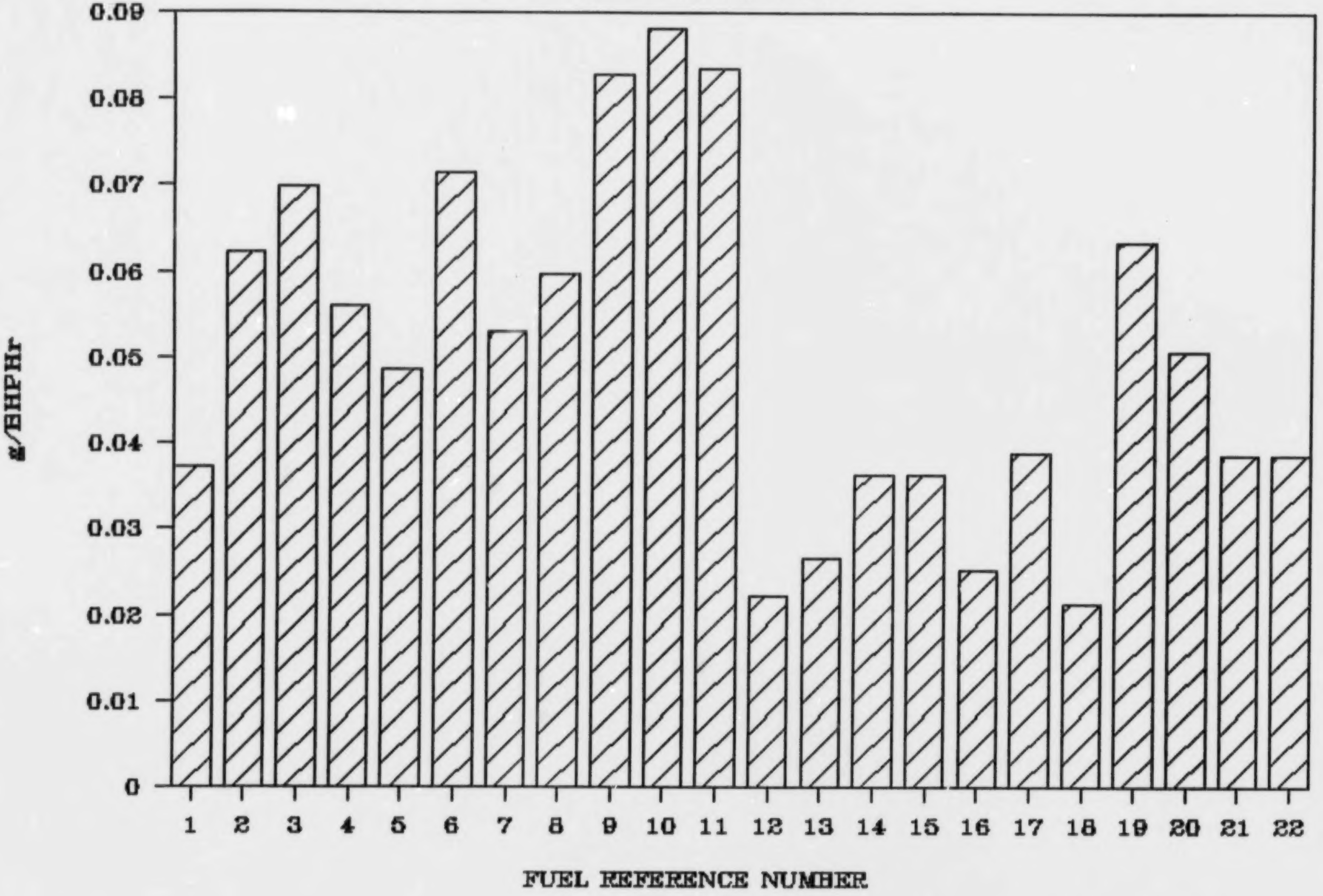
SOLUBLE PARTICULATES (g/BHPHr)

1400RPM/25%LOAD



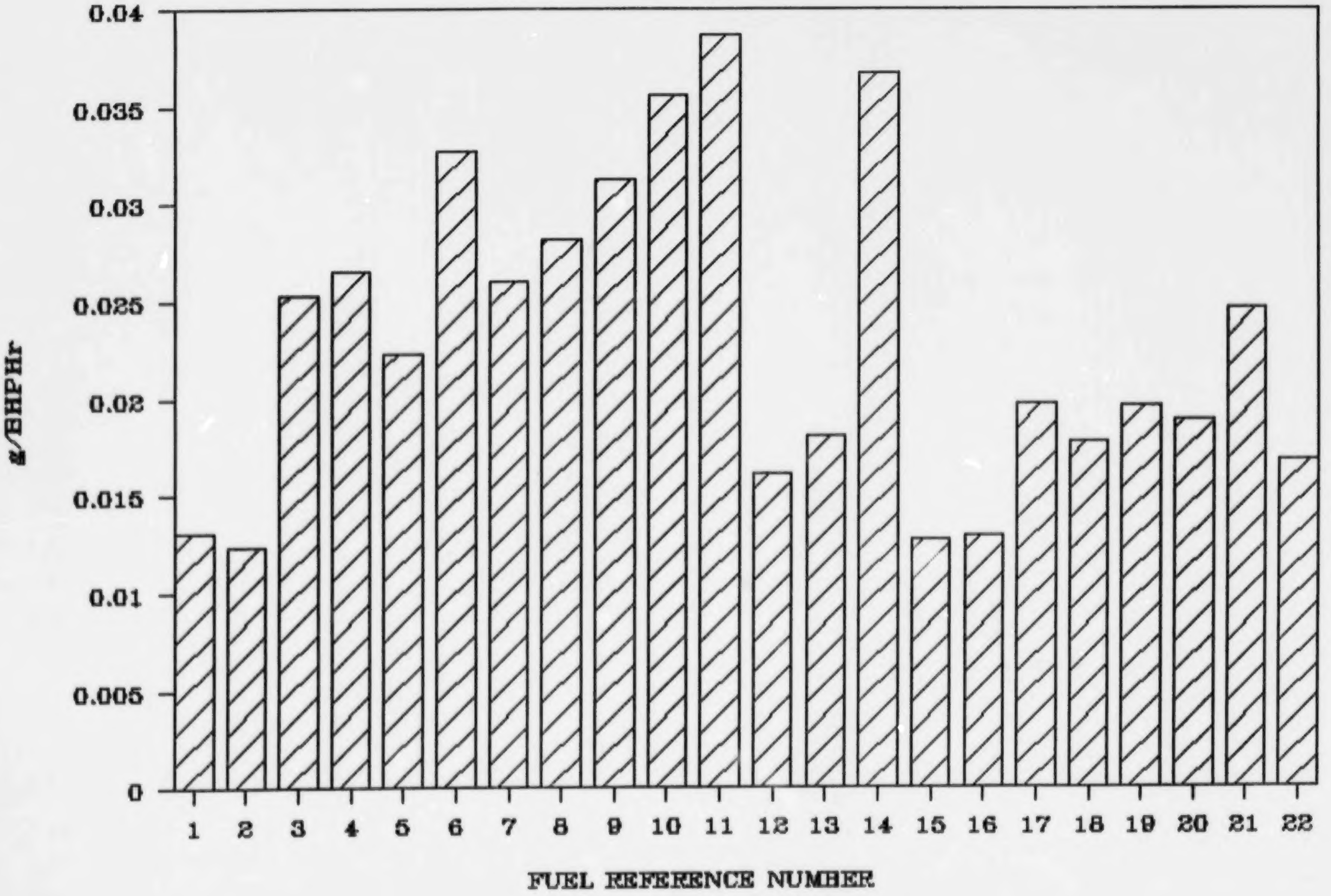
SOLUBLE PARTICULATES (g/BHPHr)

1800RPM/75%LOAD



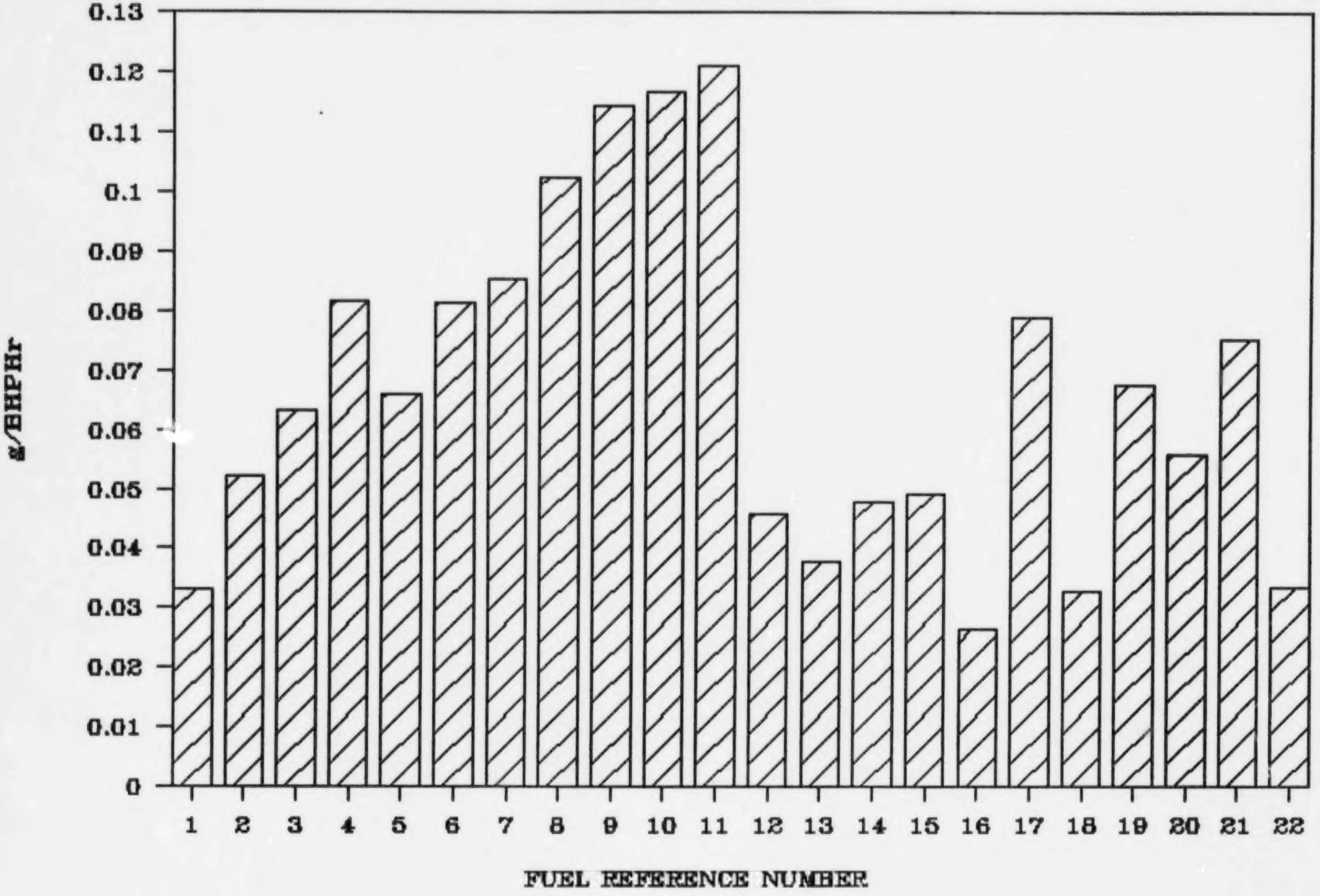
SOLUBLE PARTICULATES (g/BHPHr)

1600RPM/100%LOAD



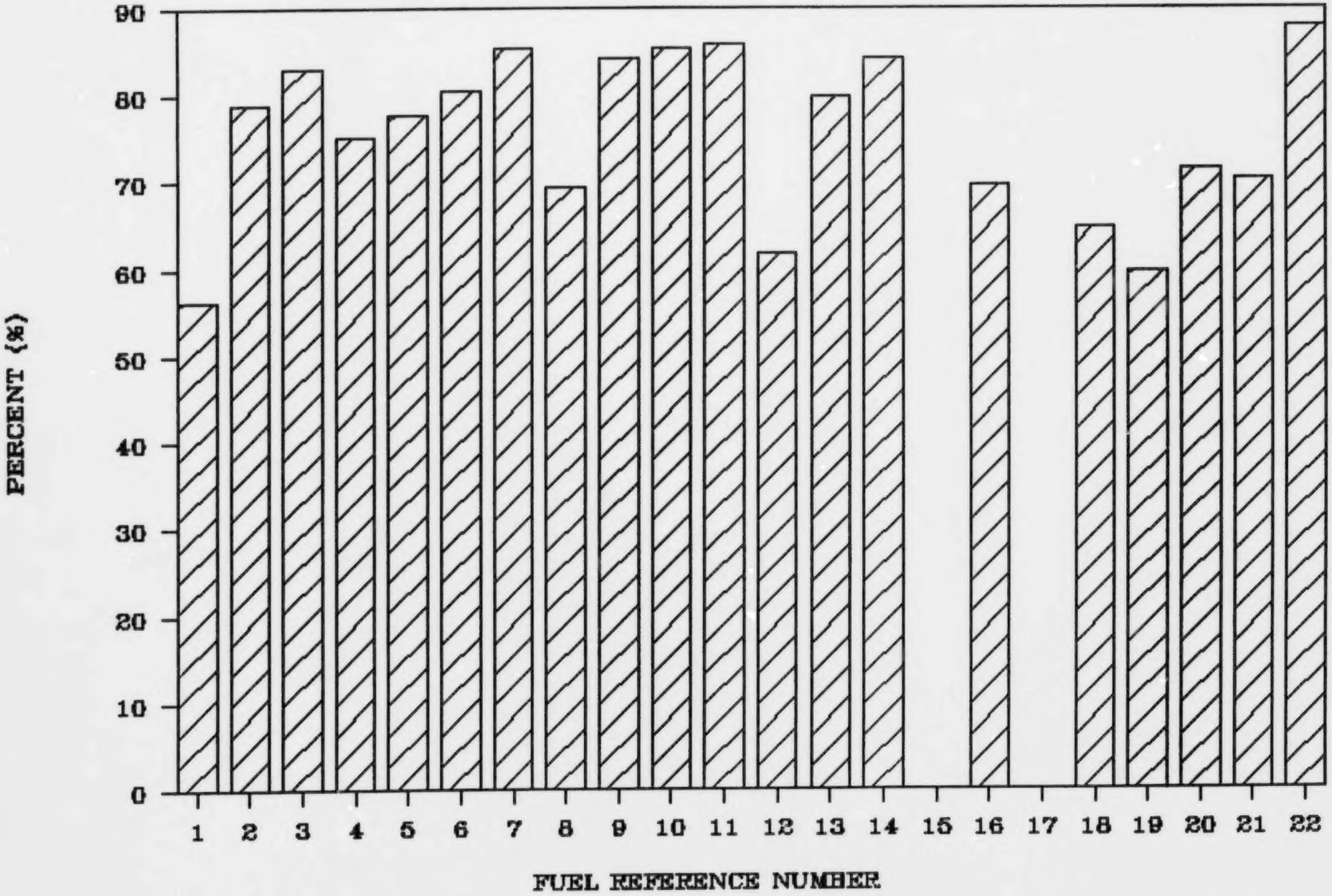
SOLUBLE PARTICULATES (g/BHPHr)

2200RPM/100%LOAD



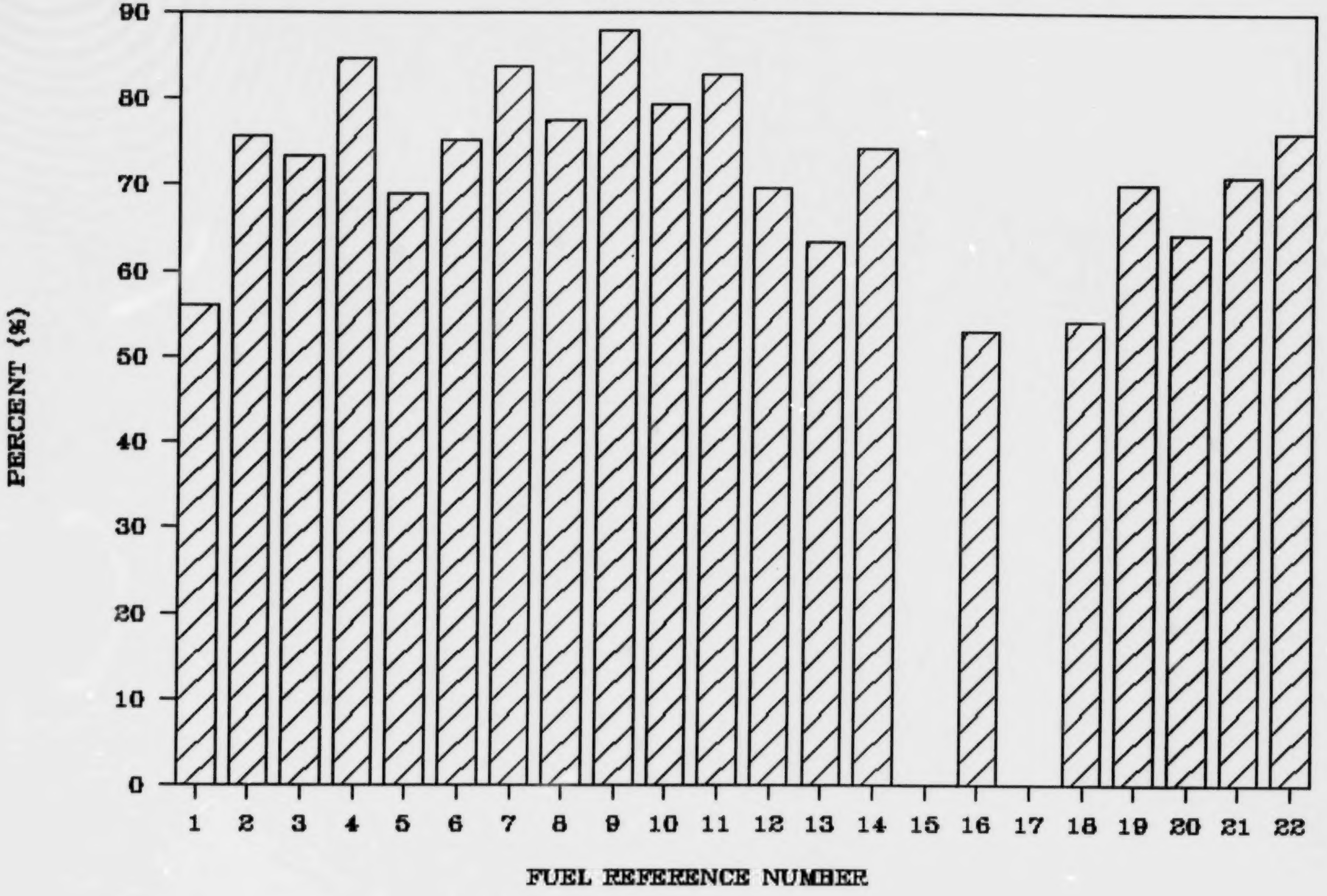
SOLUBLE PARTICULATES (%)

IDLE



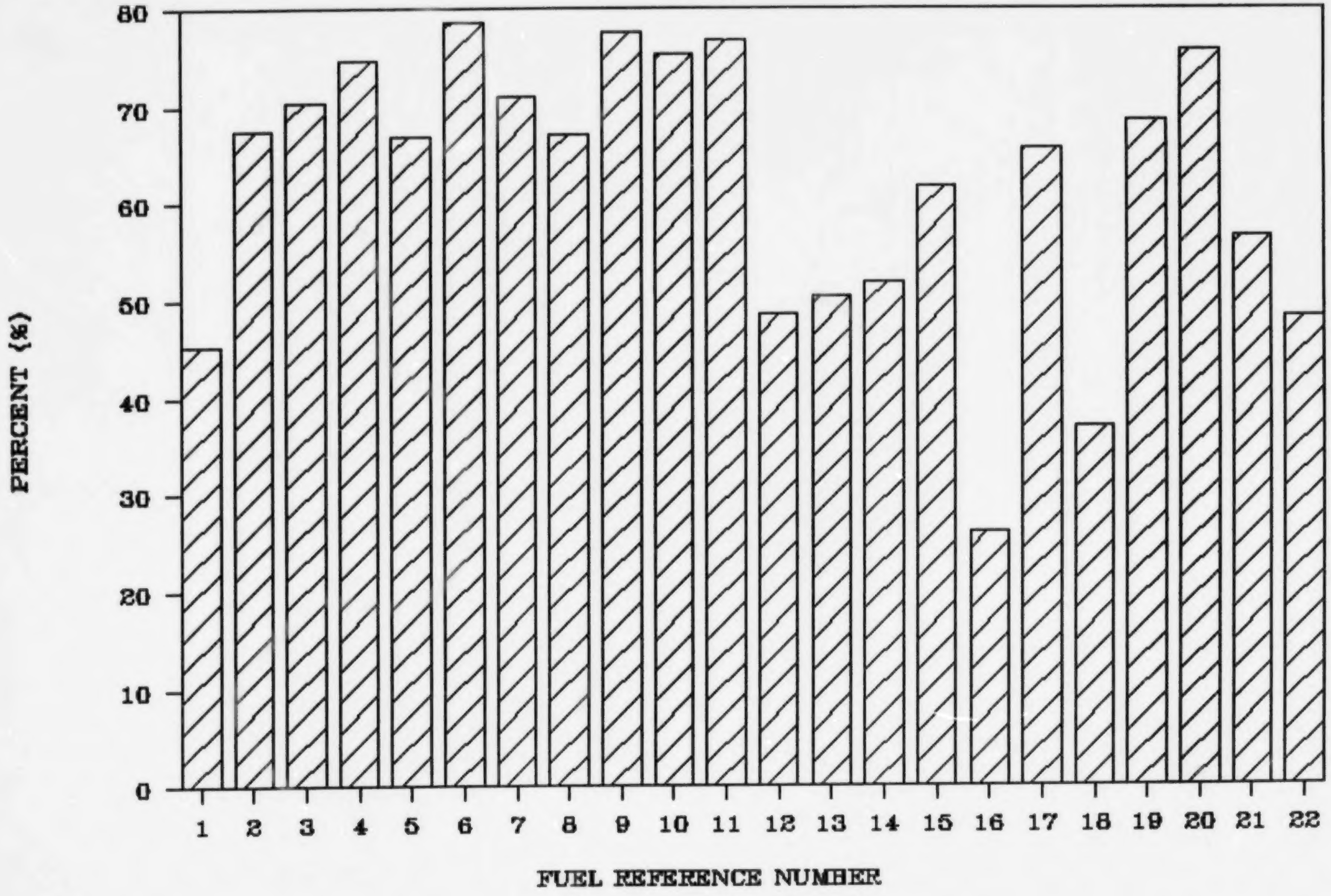
SOLUBLE PARTICULATES (%)

1400RPM/25%LOAD



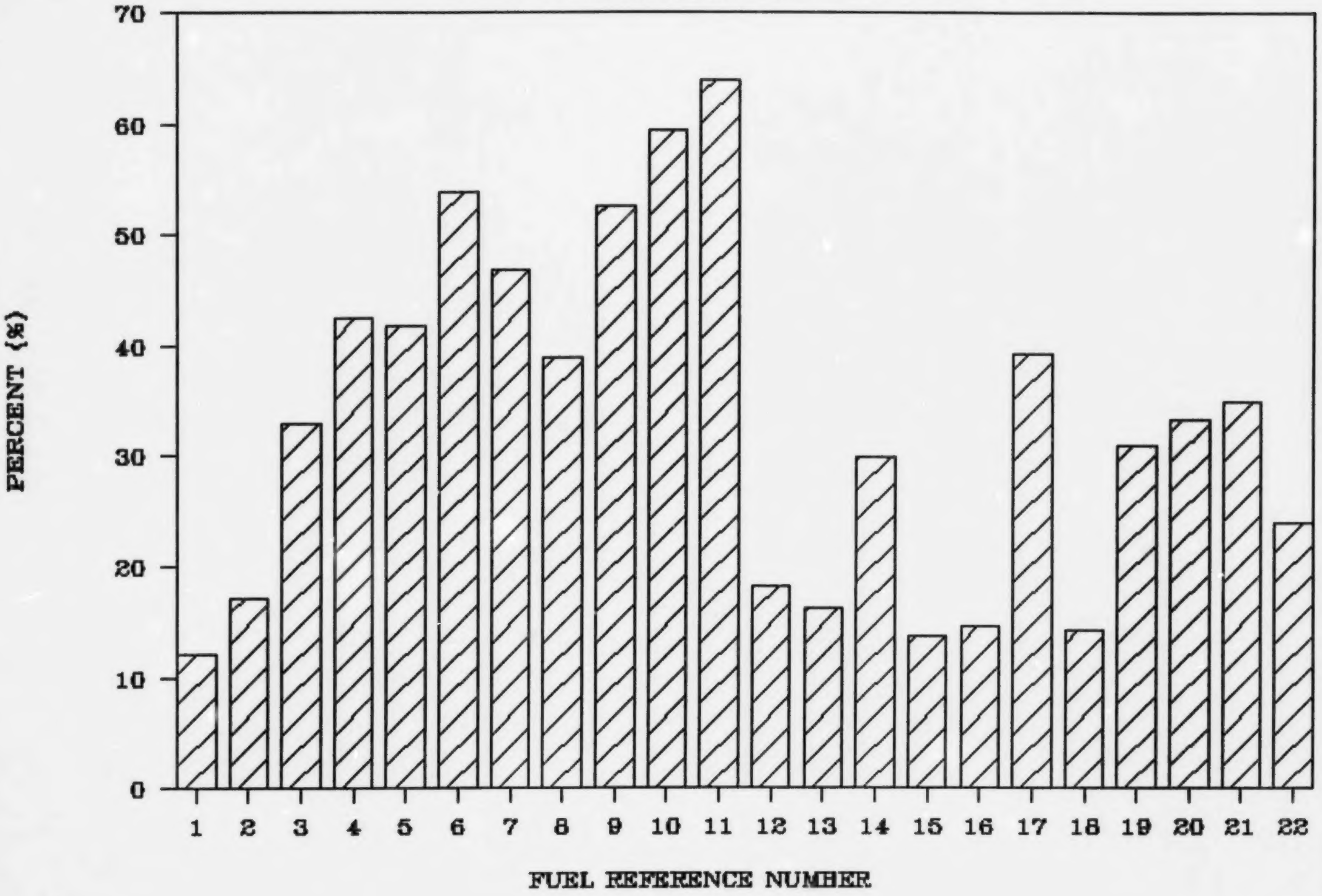
SOLUBLE PARTICULATES (%)

1800RPM/75%LOAD



SOLUBLE PARTICULATES (%)

1600RPM/100%LOAD



SOLUBLE PARTICULATES (%)

2200RPM/100%LOAD